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SCIENTIFIC SYNTHESIS ON THE IMPACTS OF UNDERWATER NOISE ON MARINE AND COASTAL BIODIVERSITY AND HABITATS

Note by the Executive Secretary

1. Significant progress has been made in analysing the impacts of underwater noise on marine and coastal biodiversity, including through initiatives under the Convention on Migratory Species, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS), the International Whaling Commission (IWC), and the International Maritime Organization (IMO). In paragraph 12 of decision X/29, the Conference of the Parties to the Convention on Biological Diversity recognized the role of the Convention in supporting global cooperation, and requested the Executive Secretary, in collaboration with Parties, other Governments, and relevant organizations, to compile and synthesize available scientific information on anthropogenic underwater noise and its impacts on marine and coastal biodiversity and habitats, and to make such information available for consideration at a meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) as well as to other relevant organizations prior to the eleventh meeting of the Conference of the Parties.

2. Pursuant to this request, the Secretariat of the convention commissioned a scientific synthesis on the impacts of underwater noise on marine and coastal biodiversity and habitats.

3. An earlier draft of this report was circulated for peer-review through notification SCBD/STTM/DC/RH/VA/78671 (2012-012) dated 23 January 2012 and comments were taken into account in finalizing the report.

* UNEP/CBD/SBSTTA/16/1.

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SCIENTIFIC SYNTHESIS ON THE IMPACTS OF UNDERWATER NOISE ON MARINE AND COASTAL BIODIVERSITY AND HABITATS

EXECUTIVE SUMMARY

<ins>Introduction and Background</ins>

1. **The underwater world is subject to a wide array of human-made noise from activities such as commercial shipping, oil and gas exploration and the use of various types of sonar**. Human activity in the marine environment is an important component of oceanic background noise and can dominate the acoustic properties of coastal waters and shallow seas. Human activities introduce sound into the marine environment either intentionally for a specific purpose (e.g., seismic surveys) or unintentionally as a by-product of their activities (e.g., shipping or construction). Anthropogenic noise can be broadly split into two main types: impulsive and non-impulsive sounds. The level of human activity and corresponding noise production in the marine environment is predicted to rise over the coming decades as maritime transportation and the exploration and extraction of marine resources continues to grow.

2. **Anthropogenic noise in the marine environment has increased markedly over the last 100 or so years as the human use of the oceans has grown and diversified**. Technological advances in vessel propulsion and design, the development of marine industry and the increasing and more diverse anthropogenic use of the marine environment have all resulted in a noisier underwater realm. Long-term measurements of ocean ambient sound indicate that low frequency anthropogenic noise has been increased, primarily due to commercial shipping. As well as an increase in commercial shipping the last half century has also seen an expansion of industrial activities in the marine environment including oil and gas exploration and production, commercial fishing and more recently the development of marine renewable energy. In coastal areas the increase in the number of small vessels is also a cause for localised concern where they can dominate some coastal acoustic environments such as partially enclosed bays, harbours and estuaries.

3. **Anthropogenic noise has gained recognition as an important stressor for marine life and is now acknowledged as a global issue that needs addressing**. The impacts of sound on marine mammals have received particular attention, especially the military's use of active sonar, and industrial seismic surveys coincident with cetacean mass stranding events. Extensive investigation mainly over the last decade by academia, industry, government agencies and international bodies has resulted in a number of reviews of the effects of sound on marine fauna. The issue of underwater noise and its effects on marine biodiversity has received increasing attention at the international level with recognition by a number of international and regional agencies, commissions and organisations including the Convention of Migratory Species (CMS), the International Whaling Commission (IWC), the United Nations (U.N. General Assembly (UNGA) and U.N. Convention on the Law of the Sea (UNCLOS)), the European Parliament and European Union, the International Union for Conservation of Nature (IUCN), the International Maritime organization (IMO), the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM).

<ins>The Importance of Sound to Marine Animals</ins>

4. **Sound is extremely important to many marine animals and plays a key role in communication, navigation, orientation, feeding and the detection of predators**. The distinctive properties of underwater sound and the limitations of other senses such as vision, touch, taste and smell in the marine environment in terms of range and speed of signal transmission mean that sound is the preferential sensory medium for a large proportion of marine animals. Almost all marine vertebrates rely to some extent on sound for a wide range of biological functions. Marine mammals use sound as a primary means for underwater communication and sensing. They emit sound to communicate about the presence of danger, food, a conspecific or other animal, and also about their own position, identity, and

reproductive or territorial status. Many other marine taxa also rely on sound on a regular basis including teleost fish and invertebrates such as decapod crustaceans. Fish utilize sound for navigation and selection of habitat, mating, predator avoidance and prey detection and communication. Impeding the ability of fish to hear biologically relevant sounds might interfere with these critical functions. Although the study of invertebrate sound detection is still rather limited, based on the information available it is becoming clear that many marine invertebrates are sensitive to sounds and related stimuli. However, the importance of sound for many marine taxa is still rather poorly understood and in need of considerable further investigation.

<u>The Impacts of Underwater Noise on Marine Biodiversity</u>

5. **A variety of marine animals are known to be affected by anthropogenic noise**. Negative impacts for least 55 marine species (cetaceans, teleost fish, marine turtles and invertebrates) have been reported in scientific studies to date.

6. **A wide range of effects of increased levels of sound on marine fauna have been documented** both in laboratory and field conditions. The effects can range from mild behavioural responses to complete avoidance of the affected area, masking of important acoustic cues, and in some cases serious physical injury or death. Low levels of sound can be inconsequential for many animals. However, as sound levels increase the elevated background noise can disrupt normal behaviour patterns leading to less efficient feeding for example. Masking of important acoustic signals or cues can reduce communication between con-specifics and may interfere with larval orientation which could have implications for recruitment. Some marine mammals have tried to compensate for the elevated background noise levels by making changes in their vocalisations. Intense levels of sound exposure have caused physical damage to tissues and organs of marine animals, and can lead to mortality, with lethal injuries of cetaceans documented in stranded individuals caught up in atypical stranding events. Lower sound levels have been shown to cause permanent or temporary loss of hearing in marine mammals and fish. Behavioural responses such as strong avoidance of the sound source can lead to habitat displacement. Some marine animals, such as beaked whales are particularly susceptible to anthropogenic sound, and some populations have experienced declines for years after a sonar-induced stranding event.

7. **There are increasing concerns about the long-term and cumulative effects of noise on marine biodiversity**. The long-term consequences of chronic noise pollution for individuals and populations are still mainly unknown. Potential long-term impacts of reduced fitness and increased stress leading to health issues have been suggested. There is also growing concern of the cumulative effects of anthropogenic sound and other stressors and how this can affect populations and communities. Although there is currently little empirical evidence for noise effects on marine populations, acoustic studies for terrestrial vertebrates indicate that features such as fitness and reproductive success can be compromised. The additional threat of living in a noisy environment may push already highly stressed marine animals into population decline with subsequent effects on marine communities and biodiversity.

<u>Acoustic Research and Future Research Needs</u>

8. **Research is required to better understand the impacts of anthropogenic sound on marine biodiversity.** The lack of scientific knowledge regarding the issue is also one of the most important limitations for effective management at the present time. There are high levels of uncertainty for noise effects on all marine taxa,. Detailed research programmes of noise effects on species, populations, habitats and ecosystems plus also cumulative effects with other stressors need to be put in place or consolidated where they already exist. However, the extensive knowledge gaps also mean that prioritisation will be required. Recommended priorities for research include species that are already highly threatened, endangered or particularly vulnerable through a combination of multiple stressors and intrinsic characteristics, but also representative groups of understudied taxa. Current knowledge for some faunal groups such as teleost fish, elasmobranch fish, marine turtles, seabirds and invertebrates is particularly lacking. Other priorities for acoustic-related research are the identification and protection of critical habitats that endangered or threatened marine species depend upon for important activities such as foraging or spawning. Marine species that support commercial fisheries should also be assessed for

susceptibility to noise pollution and the issue of anthropogenic noise considered for fisheries management plans.

Management and Mitigation of Underwater Noise

9. **There is a need to scale up the level of research and management efforts, to significantly promote greater awareness of the issue and to take measures minimise our noise impacts on marine biodiversity**. A number of current or proposed large-scale research programmes are addressing a range of issues with a focus on marine mammals. Existing or proposed management frameworks involving noise pollution also need to be tested and refined accordingly in a range of scenarios.

10. **Effective management of anthropogenic noise in the marine environment should be regarded as a high priority for action at the national and regional level** through the use of up to date mitigation measures based on the latest scientific understanding of the issue for marine species and habitats. Mitigation and management of anthropogenic noise through the use of spatio-temporal restrictions (STR) of activities has been recommended as the most practical and straightforward approach to reduce effects on marine animals. A framework for the implementation of STR's is available for use by national and regional bodies to ensure that acoustic issues are considered in future marine spatial planning.

11. **Mitigation of marine noise in the oceans** is in place for industrial and military activities in some regions of the world through the use of measures and guidelines. However, critical analysis of this guidance has identified a number of significant limitations including the considerable variation in standards and procedures between regions or navies. Mitigation of anthropogenic sound levels in the marine environment require regular updating to keep in touch with changes in acoustic technology and the latest scientific knowledge of marine species such as acoustic sensitivity and population ecology. There have been calls for the setting of global standards for the main activities responsible for producing anthropogenic sound in the oceans. Progress is being made with regard to commercial shipping and quieting but standards for naval sonar or seismic surveys are also required to reduce impacts on marine species.

New Challenges

12. **New challenges such as global changes in ocean parameters** (e.g. acidity and temperature) are also likely to have consequences for marine noise levels at a range of geographic scales through changes in sound absorption and the retreat of Arctic sea ice opening up waters for exploration and resource extraction. Preliminary modelling of projected changes in acidity caused by ocean acidification suggests that particularly noisy regions that are also prone to reduced sound absorption should be recognised as hotspots where mitigation and management is probably most needed. Further research is needed to confirm these predictions. Previously relatively quiet areas of the oceans such as the Arctic are also highly likely to be exposed to increased levels of anthropogenic sound as the sea ice coverage decreases, through exploration and exploitation, with potentially significant effects on marine biodiversity. Management frameworks for the Arctic need to consider anthropogenic noise as an important stressor alongside others when deciding the extent of activities permitted in these waters.

I BACKGROUND AND INTRODUCTION

As human populations have grown and become more industrialised over the last two centuries the marine environment has been subjected to increasing levels of underwater noise from anthropogenic sources. Technological advances in vessel propulsion and design, the development of marine industry and the increasing and more diverse anthropogenic use of the marine environment have all resulted in a noisier underwater realm. Increased levels of underwater noise can have significant effects on marine biodiversity and have been shown to cause physical injury, alter animal behaviour and have more subtle physiological effects on marine organisms. The rising levels of anthropogenically enhanced background or ambient noise can also mask important acoustic cues and signals between conspecific marine fauna.

Detecting and emitting underwater sound is extremely important for marine mammals[1 2] and many fish[3] but also for some invertebrates[4].

Initial concerns of the potential negative effects of anthropogenic noise on marine life were raised by the scientific community in the 1970's and research on the subject expanded in the 1980's[5]. The impacts of sound on marine mammals have received particular attention, especially the military's use of active sonar, and industrial seismic surveys coincident with cetacean mass stranding events[6]. Extensive investigation mainly over the last decade by academia, industry, government agencies and international bodies has resulted in a number of reviews of the effects of sound on marine fauna, and for mammals and fish in particular [7 8 9 10]. Over the last decade the issue of underwater noise and its effects on marine biodiversity have received increasing attention at the international level. The Convention on the Conservation of Migratory Species of Wild Animals (CMS), the International Whaling Commission (IWC), the United Nations General Assembly (UNGA), the European Parliament and European Union, the International Union for Conservation of Nature (IUCN), the International Maritime Organization (IMO), the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, the Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM), the Agreement on the Conservation of Cetaceans in the Black Sea Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) and the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) have all considered the negative effects of anthropogenic underwater noise through the adoption of resolutions or recognition of the issue for the marine environment.

However, although there have been major advances in the knowledge of the main types of anthropogenic sound in the ocean and the effects of these sounds on marine biodiversity over the last few decades there are still large and substantial gaps in our knowledge of underwater noise and the impacts it has on marine species and populations. Existing mitigation measures used by marine industries and the military may therefore not be very effective and are essentially still at a developmental stage. The use of the precautionary principle is therefore regarded as the most sensible and best-practice approach when dealing with a situation with insufficient data available. Although noise is a recognized form of pollution, sources of noise in the marine environment are not regulated at an international level. There has been progress made at the regional level (e.g., OSPAR, ASCOBANS, ACCOBAMS, HELCOM) in terms of regulatory frameworks for the prevention of pollution and preservation of biodiversity that provide an

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[1] Berta, A., Sumich, J.L. and Kovacs, K.M. (2006). Marine mammals - evolutionary biology 2nd edition. Elsevier and Academic Press, San Diego, 547 pp.

[2] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp.

[3] Popper, A.N. 2003. Effects of Anthropogenic Sounds on Fishes. Fisheries, 28 no 10: 24-31.

[4] Popper, A.N., Salomon, M. and Kenneth, W.H. (2001). Acoustic detection and communication by decapod crustaceans. J. Comp. Physiol. A., 187: 83-89.

[5] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[6] NRDC, 2005. Sounding the depths II: The rising toll of sonar, shipping and industrial ocean noise on marine life. Natural Resources Defense Council November 2005.

[7] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp.

[8] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

[9] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[10] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

existing mandate for the control of noise pollution[11]. The development of indicators and standards for underwater noise is also currently receiving attention in some regions[12].

This study was undertaken, with the financial support from the Government of Japan through Japan Biodiversity Fund, pursuant to the request made by the Conference of the Parties to the Convention at its tenth meeting in decision X/29 (paragraph 12) with the kind financial support of the Japan Biodiversity Fund. In this decision, the Conference of Parties to the Convention on Biological Diversity, "*…requests the Executive Secretary, in collaboration with Parties, other Governments, and relevant organizations, to compile and synthesize available scientific information on anthropogenic underwater noise and its impacts on marine and coastal biodiversity and habitats, and make such information available for consideration at a future meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) as well as other relevant organizations prior to the eleventh meeting of the Conference of the Parties"* [13].

Likewise, in decision X/13 (paragraph 2 (b)), the Conference of the Parties requested the Subsidiary Body on Scientific, Technical and Technological Advice to take into account, in the implementation of the programmes of work on protected areas and on marine and coastal biodiversity, the impact of ocean noise on marine protected areas and to consider the scientific information on underwater noise and its impacts on marine and coastal biodiversity and habitats that will be made available by the Executive Secretary prior to the eleventh meeting of the Conference of the Parties.

OVERVIEW OF UNDERWATER SOUND

Sound is a mechanical disturbance that travels through an elastic medium (e.g., air, water or solids)[14]. Sound is created if particles in such a medium are displaced by an external force and start oscillating around their original position. These oscillating particles will also set neighbouring particles in motion as the original disturbance travels through the medium. This oscillation can be slow or fast producing what we perceive as low pitch sounds (slow oscillation) or high pitch sounds (fast oscillation). The concept of frequency is used to put values on these oscillations which establish the oscillations per second that are produced in the particles. The units for measuring oscillations are Hertz (Hz). Humans can hear frequencies between 20 Hz to 20 kHz, but the audible spectrum for marine mammals and other species can extend far beyond the human hearing range. Sounds outside the human hearing range are referred to as infrasound (below 20 Hz) and ultrasound (above 20 kHz).

While the ears of mammals primarily sense pressure changes, the lateral line systems and ears of fish can also sense movement of particles directly. Particle motion refers to the vibrations of the molecules around an equilibrium state and can be quantified by measuring either velocity or acceleration of the particles.

Water is an excellent medium for sound transmission because of its high molecular density. Sound travels almost five times faster through sea water than through air (about 1500 vs. 300 m/s), and low frequencies can travel hundreds of kilometres with little loss in energy[15], thereby enabling long distance

[11] Scott, K. 2007. Sound and Cetaceans: A Regional Response to Regulating Acoustic Marine Pollution. Journal of International Wildlife Law and Policy, 10:175–199

[12] Tasker, M.L, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

[13] See http://www.cbd.int/decision/cop/?id=12295

[14] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[15] Urick, R.J. 1983. Principles of Underwater Sound. McGraw-Hill Co, New York.

communication, but also a long-distance impact of noise on aquatic animals[16]. Sound propagation is affected by four main factors: the frequency of the sound, water depth, and density differences within the water column, which vary with temperature and pressure. Therefore the sound arriving at an animal is subject to propagation conditions that can be quite complex, which can in turn significantly affect the characteristics of arriving sound energy[17].

Sound levels or sound pressure levels (SPL) are referred to in decibels (dB). However, the dB is not an absolute unit with a physical dimension, but is instead a relative measure of sound pressure with the lower limit of human hearing corresponding to 0 dB in air. Underwater dB-levels are different from above water dB-levels[18]. Sound pressure levels above water are referenced to 20 µPa, while underwater they are referenced to 1 µPa[19]. There are different measurements and units to quantify the amplitude and energy of the sound pressure level[20 21]:

- **Peak-to-peak** (p-p) is the difference of pressure between the maximum positive pressure and the maximum negative pressure in a sound wave. Peak-to-peak SPLs are usually used to describe short, high intensity sounds where the rms-sound pressure value could underestimate the risk of acoustic trauma;
- The **root-mean-square**-(RMS) value is calculated as the square-root of the mean-squared pressure of the waveform. RMS sound values can change significantly depending on the time duration of the analysis. The values of a continuous signal measured in RMS or in peak value usually differ by 10-12 dB;
- The **Spectrum** of a sound, provides information on the distribution of the energy contained in the signal or the 'frequency content' of a sound. The term bandwidth describes the frequency range of sound. A normalised bandwidth of 1 Hz is standard practice in mathematical analysis of sound, while 1/3 octave bandwidths are most common in physical analysis. Spectra therefore need some indication of the analysis bandwidth;
- The **Sound Exposure Level** (SEL) is a measure of the energy of a sound and depends on both amplitude and duration. SELs are considered useful when making predictions about the physiological impact of noise.
- **Transmission loss** refers to the loss of acoustic power with increasing distance from the sound source. Sound pressure diminishes over distance due to the absorption and geometrical spreading of waves. In an ideal scenario, without reflections or obstacles, the sound pressure diminishes by a factor of 1 over the considered distance (1/r, where r = radius from the source). In realistic scenarios, due to differing layers of water, the propagation of sound and its attenuation may be very different.

[16] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

[17] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[18] Finfer, D.C. et al. (2008) Issues relating to the use of 61.5 conversion factor when comparing airborne and underwater anthropogenic noise levels. Appl. Acoust. 69, 464–471

[19] micro-Pascal or one millionth of one Pascal (1 Pascal is equal to the force of 1 Newton applied uniformly over the surface of 1 square metre and is abbreviated 1 Pa)

[20] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp.

[21] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029.

For example, the reduction of sound pressure could diminish if the sound is channelled due to seabed topography and/or water column stratification. The effects of topography and the characteristics of the water column can induce very complex situations[22], which should be taken into account when establishing correct measurements of sound impacts. Absorption losses are negligible for low frequencies (<1 kHz) but can be significant for high frequencies;

- **Source Levels** (SL) describe the level of sound pressure referred to the nominal distance of 1 metre from the source[23].

There is currently no scientific consensus for expressing sound levels in marine acoustics. Ideally all values should be converted to the same values (points) of reference, averaged in the same time intervals and this should be expressed in all measures[24]. RMS values are useful for relatively long sounds but less effective for brief sounds such as pile-driving strikes and echolocation clicks of whales[25]. Peak-to-peak values in the amplitude waveform provide an alternative measure, but comparisons between peak-to-peak and RMS levels are difficult[26].

Lastly, it is important to define the terms ‘sound’, ‘noise’ and ‘signal’. Sound is an allusive term for any acoustic energy. Noise is a type of unwanted sound for the receiver. The opposite of noise is a signal; i.e. a sound that contains some useful or desirable information. A particular sound can therefore be noise to one receiver and a signal to others[27].

NATURAL UNDERWATER NOISE

There is a range of natural sound sources in the marine environment which can be of physical or biological origin. Natural physical phenomena that contribute to underwater ambient noise include wind, waves, and swell patterns; bubbles; currents and turbulence; earthquakes; precipitation and ice cover and activity[28]. There are also specific acoustic events such as sub-sea volcanic eruptions, earthquakes and lightning strikes with the potential to affect marine life. Wind-driven waves are the dominant natural physical noise source in the marine environment. In the absence of anthropogenic and biological sound ambient noise is wind dependent over an extremely broad frequency band from below 1 Hz to at least 100 kHz[29]. In the open ocean underwater noise levels can be increased by more than 20 dB (10 Hz to 10 kHz band) by spilling and plunging breakers[30] while precipitation can raise ambient noise levels by up to 35

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[22] Bain, D.E. & Williams, R. 2006: Long-range effects of airgun noise on marine mammals: Responses as a function of received sound level and distance. – IWCSC/ 58E35.

[23] Urick, R.J. 1983. Principles of Underwater Sound. McGraw-Hill Co, New York.

[24] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

[25] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

[26] Madsen, R.T. (2005) Marine mammals and noise: Problems with root mean square sound pressure levels for transients. J. Acoust. Soc. Am. 117, 3952–3957

[27] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

[28] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124.

[29] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124.

[30] Wilson, O.B. Jr., Wolf, S.N. and Ingenito, F. 1985. Measurements of ambient noise in shallow water due to breaking surf. J. Acoust. Soc. Am. 78: 190-195.

dB across a broad band of frequencies (100 Hz to more than 20 kHz)[31]. Closer to shore sounds from pack ice cracking may increase underwater noise levels by as much as 30 dB. Seismic waves from undersea earthquakes can be up to 30–40 dB above ambient noise levels, with a sharp onset, and can last from a few seconds to several minutes[32].

Marine mammals (cetaceans and pinnipeds) produce sounds that are used for communication, orientation and navigation, and foraging. Sounds range from the 10 Hz low-frequency calls of blue whales to the ultrasonic clicks of more than 200 kHz in certain offshore dolphins[33]. Source levels of click sounds used by sperm whales in navigation and foraging can be as high as 235 dB re 1µPa peak-to-peak[34]. Baleen whales use low frequency sound for long distance communication[35] over hundreds of kilometres[36][37]. Most toothed whales (odontocetes) emit three main types of sounds; tonal whistles, short duration pulsed sounds used for echolocation and less distinct pulsed sounds such as cries, grunts or barks[38]. Odontocete echolocation clicks are highly directional forward-projecting pulsed sounds of high intensity and frequency. Some species of seal produce strong underwater sounds that may propagate for great distances[39]. Many marine fish species produce sound for communication[40]. The low frequency sounds created by fish can make a significant contribution to ambient noise[41]. Fish can produce sounds as individuals, but also in choruses[42] and the increase in low-frequency noise can be as much as 20 - 30 dB in the presence of chorusing fishes[43]. The dominant source of ambient noise in tropical and sub-tropical waters are snapping shrimp, which can increase ambient noise levels by 20 dB in the mid-frequency band[44]. In addition to shrimp a number of other invertebrates contribute to ambient reef noise, including squid[45], crabs[46], lobsters[47] and urchins[48].

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[31] Nystuen, J.A. and Farmer, D.M. 1987. The influence of wind on the underwater sound generated by light rain. J. Acoust. Soc. Am. 82: 270-274

[32] Shreiner et al., 1995

[33] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[34] Møhl , B., Wahlberg, M., Madsen, P.T., Heerfordt, A., and Lundt, A. (2003). The mono-pulse nature of sperm whale clicks. J. Acoust. Soc. Am., 114: 1143-1154.

[35] Tyack, P. 2008. Implications for marine mammals of large-scale changes in the marine acoustic environment. Journal of Mammalogy 89: 549-558.

[36] Stafford, K. M., C. G. Fox, and D. S. Clark. 1998. Long-range acoustic detection and localization of blue whale calls in the northeast Pacific. Journal of the Acoustical Society of America 104:3616–3625

[37] Watkins, W. A., et al.,. 2000. Whale call data for the North Pacific: November 1995 through July 1999 occurrence of calling whales and source locations from SOSUS and other acoustic systems. Woods Hole Oceanographic Institution Technical Report 2000– 02:1–156.

[38] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp (Table 7.2)

[39] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[40] Bass, A. H. & Ladich, F. (2008). Vocal–acoustic communication: From neurons to brain. In Fish Bioacoustics (Webb, J. F., Fay, R. R. & Popper, A. N., eds), pp. 253–278. New York: Spinger Science+Business Media, LLC.

[41] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[42] Cato DH, McCauley RD. 2002. Australian research in ambient sea noise. Acoust Aust 30:13–20

[43] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[44] Ibid

[45] Iversen, R.T.B., Perkins, P.J., Dionne, R.D. 1963. An indication of underwater sound production by squid. Nature 199, 250–251.

[46] Burkenroad, M.D., 1947. Production of sound by the Fiddler Crab, Uca pugilator Bosc, with remarks on its nocturnal and mating behavior. Ecology 28, 458–462.

[47] Patek, S.N., 2001. Spiny lobsters stick and slip to make sound. Nature 411, 153.

[48] Radford, C., Jeffs, A., Tindle, C., Montgomery, J.C., 2008. Resonating sea urchin skeletons create coastal choruses. Mar. Ecol. Prog. Ser. 362, 37–43.

THE IMPORTANCE OF SOUND FOR MARINE ORGANISMS

Sound is an important sensory modality for many marine animals[49]. The distinctive properties of underwater sound mentioned previously and the limitations of other senses such as vision, touch, taste and smell in the marine environment in terms of range and speed of signal transmission mean that sound is the preferential sensory medium for a large proportion of marine animals. A range of marine taxa, including marine mammals, many fish and some invertebrates has developed special organs and mechanisms for detecting and emitting underwater sound. To maximise the use of the underwater acoustic environment marine mammals have developed broader hearing frequency ranges than are typically found in terrestrial mammals[50]. Marine fish possess two sensory systems for acoustic and water motion detection; the inner ear and the lateral line system. Marine fauna utilise and hear underwater sound in different ways[51]. Baleen whales, most fishes, sea turtles, and invertebrates hear best at lower frequencies, while the dolphins and porpoises, those species that have been studied, can hear ultrasonic frequencies above human hearing range[52] [53] [54] [55] [56]. Marine fishes and invertebrates are also sensitive to acoustic particle motion, in addition to acoustic pressure, to assess their environment[57] [58].

Almost all marine vertebrates rely to some extent on sound for a wide range of biological functions, including the detection of predators and prey, communication and navigation[59] [60]. Marine mammals use sound as a primary means for underwater communication and sensing[61]. They emit sound to communicate about the presence of danger, food, a conspecific or other animal, and also about their own position, identity, and reproductive or territorial status[62]. Underwater sound is especially important for odontocete cetaceans that have developed sophisticated echolocation systems to detect, localise and characterise underwater objects[63], for example, in relation to coordinated movement between conspecifics and feeding behaviour.

[49] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[50] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124.

[51] Tasker, M.L, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

[52] Budelmann, B.U. 1992. Hearing in crustaceans. Pp. 131 – 139 in D.B. Webster, R.R. Fay, and A.N.Popper, eds. The Evolutional Biology of Hearing. New York, New York: Springer-Verlag.

[53] Wartzok, D., and Ketten, D.R. 1999. Marine mammal sensory systems. Pp. 117-175 in J.E. Reynolds and S.A. Rommel (eds.) Biology of Marine Mammals. Washington, D.C., Smithsonian Institution Press.

[54] Bartol, S.M., and Musick, J.A. 2003. Sensory biology of sea turtles. Pages 79 – 102 in P.L. Lutz, J.A. Musick, and J. Wyneken , (eds.) The biology of sea turtles, Volume II. Washington, D.C, CRC Press.

[55] Au, W.W.L., and Hastings, M.C. 2008. Principles of Marine Bioacoustics. New York, New York: Springer. 679pp

[56] Webb, J.F., Popper, A.N. and Fay, R.R. (eds.) 2008. Fish bioacoustics. New York, New York: Springer. 318pp.

[57] Packard, A., Karlsen, H.E. and Sand, O. 1990. Low frequency hearing in cephalopods. Journal of Comparative Physiology, Part A, 166: 501 – 505.

[58] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

[59] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[60] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

[61] Wartzok, D., and Ketten, D.R. 1999. Marine mammal sensory systems. Pp. 117-175 in J.E. Reynolds and S.A. Rommel (eds.) Biology of Marine Mammals. Washington, D.C., Smithsonian Institution Press.

[62] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[63] Au, W.W.L. 1993. The sonar of dolphins. Springer-Verlag, New York. 277p.

Fish utilize sound for navigation and selection of habitat, mating, predator avoidance and prey detection and communication[64]. Impeding the ability of fish to hear biologically relevant sounds might interfere with these critical functions and use of the 'acoustic scene' or 'soundscape'[65] to learn about the overall environment[66]. Larval stages of coral reef fish can detect and are attracted to the sound of coral reefs thereby using reef noise as an acoustic cue for orientation[67]. Although the study of invertebrate sound detection is still rather limited, many species have mechano-sensors that have some resemblance to vertebrate ears[68] and based on the information available it is becoming clear that many marine invertebrates are sensitive to sounds and related stimuli[69]. This has been demonstrated in tropical waters where crustacean and coral larvae can respond to acoustic cues (reef noise)[70] [71]. It is also emerging that different habitats within shallow coastal environments can be characterised by the acoustic signals they produce[72] and that juvenile fish can use these signals to detect different habitats within coral reefs[73].

THE INCREASE IN ANTHROPOGENIC UNDERWATER SOUND

Over the past one hundred years there has been an unprecedented increase in the amount of anthropogenic noise emitted within the marine environment[74]. During this time the oceans have become more industrialised and noise levels associated with human activities have increased[75]. Long-term measurements of ocean ambient sound have revealed that low frequency anthropogenic noise has been increasing (Figure 1) and has been primarily attributed to commercial shipping noise[76] [77]. Combining this information with data from other studies[78], it has been suggested that low frequency ambient noise has increased by at least 20 dB from pre-industrial conditions to the present[79]. Over the past 50 years the size of the global commercial shipping fleet has almost tripled while the total gross tonnage has increased by a

[64] Simpson, S.D., Meekan, M.G., Montgomery, J., McCauley, R.D., Jeffs, A., 2005a. Homeward sound. Science 308, 221–228

[65] Slabbekoorn, H. and Bouton, N. (2008) Soundscape orientation: a new field in need of sound investigation. Anim. Behav. 76, e5–e8.

[66] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243

[67] Simpson, S.D.,Meekan, M.G.,McCauley, R.D., Jeffs, A., 2004. Attraction of settlement-stage coral reefs fishes to ambient reef noise. Mar. Ecol. Prog. Ser. 276, 263–268

[68] Popper, A.N. 2003. Effects of Anthropogenic Sounds on Fishes. Fisheries, 28 no 10: 24-31.

[69] Moriyasu et al., 2004. Effects of seismic and marine noise on invertebrates: A literature review. Canadian Science Advisory Secretariat. Research document 2004/126

[70] Vermeij MJA, Marhaver KL, Huijbers CM, Nagelkerken I, Simpson SD (2010) Coral Larvae Move toward Reef Sounds. PLoS ONE 5(5): e10660. doi:10.1371/ journal.pone.0010660

[71] Simpson SD, Radford AN, Tickle EJ, Meekan MG, Jeffs AG (2011) Adaptive Avoidance of Reef Noise. PLoS ONE 6(2): e16625. doi:10.1371/ journal.pone.0016625

[72] Kennedy EV, Guzman HM, Holderied MW, Mair JM, Simpson SD (2010) Reef generated noise provides reliable information about habitats and communities: evidence from a Panamanian case study. J Exp Mar Biol Ecol 395: 85–92

[73] Radford CA, Stanley JA, Simpson SD, Jeffs AG (2011) Juvenile coral reef fishes use sound to locate habitats. Coral Reefs, 30:295-305

[74] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

[75] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[76] Andrew RK, Howe BM, Mercer JA, Dzieciuch MA (2002) Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. Acoust Res Lett Online 3:65–70

[77] McDonald MA, Hildebrand JA, Wiggins SM, Ross D (2008) A fifty year comparison of ambient ocean noise near San Clemente Island: a bathymetrically complex coastal region off southern California. J Acoust Soc Am 124:1985–1992

[78] Ross D. 1976. Mechanics of underwater noise. Pergamon Press, New York

[79] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

factor of six[80]. In terms of the volume of cargo transported by sea, this has been approximately doubling every 20 years[81]. As well as an increase in commercial shipping the last half century has also seen an expansion of industrial activities in the marine environment including oil and gas exploration and production, commercial fishing and more recently the development of marine renewable energy.

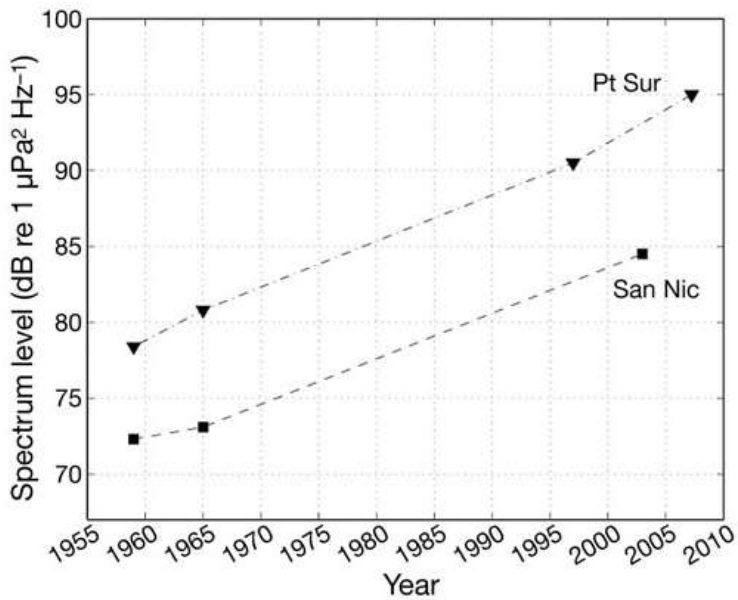

Figure 1. Historical ambient noise data from the North-eastern Pacific at 40 Hz suggest an increase of about 3 dB decade^{-1} averaged over the past 40 years. Data from the United States Navy hydrophone arrays near Point Sur and San Nicolas Island[82 83 84] and from recent measurements at these sites[85 86 87] (Adapted from Hildebrand, 2009)

In coastal areas the increase in the number of small vessels is also a cause for localised concern where they can dominate some coastal acoustic environments such as partially enclosed bays, harbours and estuaries[88].The vast majority of these vessels also use high-frequency sonar for navigation and fish-finding. The use of mid and low frequency active sonar during military exercises has expanded since their introduction in the 1960's and 1980's respectively.

[80] Ibid

[81] http://www.marisec.org/shippingfacts/worldtrade/volume-worldtrade-sea.php

[82] Wenz GM. 1961. Periodic variations in low-frequency underwater ambient noise levels. Report 1014, Navy Electronic Laboratory, San Diego, CA

[83] Wenz GM (1968) Properties of deep-water, low-frequency, ambient noise west of San Diego, California. TP 39, Naval Undersea Warfare Center, San Diego, CA

[84] Wenz GM (1969) Low-frequency deep-water ambient noise along the Pacific Coast of the United States. US Navy J Underw Acoust 19:423–444

[85] Andrew RK, Howe BM, Mercer JA, Dzieciuch MA (2002) Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. Acoust Res Lett Online 3:65–70

[86] McDonald MA, Hildebrand JA, Wiggins SM (2006) Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. J Acoust Soc Am 120: 711–718

[87] Cocker P (2008) Observations of ocean ambient noise (10 Hz to 10 kHz) at the site of a former navy listening station to the west of Point Sur, California, from January to July of 2007. Masters of Science, Naval Postgraduate School, Monterey, CA

[88] Kipple B, Gabriele C (2003) Glacier Bay watercraft noise. Technical Report NSWCCDE-71-TR-2003/522, prepared for Glacier Bay National Park and Preserve, Naval Surface Warfare Center, Bremerton, WA

II. SOURCES AND TYPES OF UNDERWATER ANTHROPOGENIC NOISE

Human activity in the marine environment is an important component of oceanic background noise[89] and can dominate the acoustic properties of coastal waters and shallow seas. Human activities introduce sound into the marine environment either intentionally for a specific purpose (e.g., seismic surveys using air guns for deep sub-bottom imaging of geological structures) or unintentionally as a by-product of their activities (e.g., shipping or construction)[90]. The main sources of anthropogenic sound in the marine environment and their acoustic properties are provided in Table 1.

Table 1. Main Sources of Anthropogenic Sound in the Marine Environment (Adapted from Hildebrand 2009 and OSPAR 2009) (Omni = omnidirectional; CW = Continuous Wave; rms = root mean square; ADD = Acoustic Deterrent Device; AHD = Acoustic Harassment Device)

Sound Source	Source Level (dB re 1 µPa-m)	Bandwidth (Hz)	Major amplitude (Hz)	Duration (ms)	Directionality
Ship shock trials (10000 lb explosive)	304	0.5 - 50	-	2000	Omni
TNT	272 – 287 Peak	2 - 1000	6 - 21	~ 1 - 10	Omni
Air-gun array	260 – 262 P-to-P	10 – 100 000	10 - 120	30 - 60	Vertically focused
Military sonar mid-frequency	223 – 235 Peak	2800 - 8200	3 500	500 - 2000	Horizontally focused
Pile driving	228 peak / 243 – 257 P-to-	20 - >20 000	100 - 500	50	Omni
Military sonar low-frequency	235 Peak	100 - 500	-	600 - 1000	Horizontally focused
Echosounders	235 Peak	Variable	Variable 1500 – 36 000	5 - 10	Vertically focused
ADDs / AHDs	132 – 200 Peak	5000 – 30 000	5000 – 30 000	Variable 15 – 500	Omni
Large vessels	180 – 190 rms	6 - > 30 000	> 200	CW	Omni
Small boats and ships	160 – 180 rms	20 - > 1000	> 1000	CW	Omni
Dredging	168 – 186 rms	30 - > 20 000	100 - 500	CW	Omni
Drilling	145 – 190 rms	10 – 10 000	< 100	CW	Omni
Acoustic telemetry SIMRAD HTL 300	190	25000 – 26500	-	CW	90 x 360°
Wind turbine	142 rms	16 – 20 000	30 - 200	CW	Omni

[89] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[90] Tasker, M.L, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

Tidal and wave energy	165 – 175 rms	10 – 50 000	-	CW	Omni

At the source, anthropogenic noise can be broadly split into two main types: impulsive and non-impulsive sounds[91]. Impulsive sound sources are typically brief, have a rapid rise time (large change in amplitude over a short time), and contain a wide frequency range, which is commonly referred to as broadband[92]. Impulsive sounds can either be a single event or are repetitive and sometimes as a complex pattern. Non-impulsive signals can be broadband or more tonal (containing one or few frequencies), brief or prolonged, continuous or intermittent, and do not have the rapid rise time (typically only small fluctuations in amplitude) characteristic of impulsive signals[93]. Examples of impulsive sounds are those from explosions, air guns, or impact pile driving, while non-impulsive sounds result from activities such as shipping, construction (e.g., drilling and dredging), or renewable energy operations. There have been a number of reviews of the physics associated with the various sound sources[94] [95] and also of the acoustic and other characteristics of each source[96] [97] [98]. A summary of each type of anthropogenic sound source is presented below.

EXPLOSIVES

Explosives are used for several purposes in the marine environment including construction, the removal of unwanted structures, ship shock trials, military warfare or practise and small charges to deter marine mammals (seal bombs), catch fish (blast fishing) or for coral mining[99]. Underwater explosions are one of the strongest point sources of anthropogenic sound in the marine environment. For example the large amount of explosives used in naval ship shock trials can produce a total Source Level of more than 300 dB (Table 1). Sound from explosions propagates equally in all directions and can be detected over great distances, sometimes across ocean basins. Underwater transmission of explosions is complex with an initial shock pulse followed by a succession of oscillating bubble pulses. Source levels can vary with the type and amount of explosives used, the water depth at which the explosion occurs and usually range from 272 to 287 dB re 1 μPa zero to peak at 1 m distance (1 - 100 lb. TNT)[100].

INDUSTRIAL ACTIVITIES

Marine construction and industrial activities include pile driving, dredging, cable laying, drilling, the operation of offshore wind farms and hydrocarbon production facilities, and the use of explosives in

[91] Ibid

[92] ANSI (American National Standards Institute) 1986. Methods of Measurement for Impulse Noise (ANSI S12.7-1986). New York: Acoustical Society of America. 14pp

[93] ANSI (American National Standards Institute). 1995. Bioacoustical Terminology (ANSI S3.20-1995). New York: Acoustical Society of America.

[94] Urick, R.J. 1983. Principles of Underwater Sound. McGraw-Hill Co, New York.

[95] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[96] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[97] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[98] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[99] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[100] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

construction and decommissioning[101]. These activities typically produce noise that has the most energy at low frequencies (20 – 1000 Hz)[102].

Pile driving is used for harbour works, bridge construction, oil and gas platform installations, and in the construction of offshore wind farm foundations. The noise produced enters the water column directly but also travels through the seabed with sound propagation varying according to the type of seabed[103]. Source levels can vary depending on the diameter of the pile and the method of pile driving (impact or vibropiling) and can reach 250 dB re 1 μPa peak to peak at 1m[104]. The frequency spectrum ranges from less than 20 Hz to more than 20 kHz with most energy around 100 - 200 Hz (Table 1).

Drilling is done from natural or man-made islands, platforms, and drilling vessels (semi-submersibles and drilling ships), producing almost continuous noise. Underwater noise levels from natural or manmade islands have been reported to be moderate (SL ~ 145 dB re 1 μPa at 1 m or less) with the main frequency content below 100 Hz[105]. Noise from fixed drilling platforms is slightly lower; e.g., 115 - 117 dB re 1 μPa at 405 and 125 metres respectively[106]. Drilling from drill-ships produces the highest levels with a maximum broadband source level of about 190 dB re 1 μPa rms at 1 m (10 Hz - 10 kHz)[107]. The ships use thrusters to remain in position, resulting in a mixture of propeller and drilling noise[108].

Dredging in the marine environment is undertaken to maintain shipping lanes, extract geological resources such as sand and gravel and to route seafloor pipelines. The activity emits continuous broadband sound during operations, mostly in the lower frequencies. One study estimated source levels ranged from 160 to 180 dB re 1 μPa at 1 m (maximum ~ 100 Hz) with a bandwidth between 20 Hz and 1 kHz[109]. Measurement of the sound spectrum levels emitted by an aggregate dredger indicated that most energy was below 500 Hz[110].

Offshore wind farms create low-frequency noise at high source levels during their construction (e.g., pile driving), but at moderate source levels during their operation[111]. Operational source levels of offshore wind farms depend on construction type, size, environmental conditions (i.e. depth, topography, sediment structure, hydrography), wind speed, and probably also the size of the wind farm[112]. Noise produced

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[101] Ibid

[102] Greene CR Jr (1987) Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea. J Acoust Soc Am 82:1315–1324

[103] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[104] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[105] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[106] McCauley (1998). Radiated underwater noise measured from the drilling rig 'Ocean General', rig tenders 'Pacific Ariki' and 'Pacific Frontier', fishing vessel 'Reef Venture' and natural sources in the Timor Sea, Northern Australia. Report prepared for Shell Australia, 54 pp.

[107] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[108] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[109] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[110] Defra/Department for Environment, Food and Rural Affairs (2003). Preliminary investigation of the sensitivity of fish to sound generated by aggregate dredging and marine construction. Project AE0914 Final Report.

[111] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[112] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

during operations has been measured from single turbines (maximum power 2 MW). Most of the sound generated was pure tones below 1 kHz, and mainly below 700Hz[113]. Operational sounds of an offshore turbine (1.5 MW) in shallow (5-10 m) waters at moderate to strong wind speeds of 12 m s^{-1} were sound pressure levels between 90 and 112 dB re 1 μPa at 110 m with most energy at 50, 160 and 200 Hz[114]. Recent measurements on four offshore wind farms (2 - 3 MW) confirmed rather low broadband received sound pressure levels (114 - 130 dB re 1 μPa) inside wind farm areas with a maximum difference in SPL to outside the wind farm of 8 dB re 1 μPa[115]. The highest source level reported for the tonal noise component during turbine operation is 151 dB re 1 μPa at 1 m, for a wind speed of 13 m s^{-1}, and at a frequency of 180 Hz[116]. There will also be some noise from maintenance (including vessels) and repair work.

Offshore tidal and wave energy turbines are a relatively recent technological development and there is currently limited information available on the acoustic signatures of these activities. Tidal turbines appear to emit broadband noise covering a frequency range from 10 Hz up to 50 kHz with significant narrow band peaks in the spectrum[117]. Depending on size, it is likely that tidal current turbines will produce broadband source levels of between 165 and 175 dB re 1μ Pa[118].

SEISMIC EXPLORATION

Marine seismic surveys are primarily used by the oil and gas industry for exploration but are also used to gather data for academic and governmental needs. There are >90 seismic vessels available globally[119], and roughly 20% of them are conducting field operations at any one time[120].

Essentially, a seismic or seabed survey involves directing a high energy sound pulse into the sea floor and measuring the pattern of reflected sound waves. A range of sound sources may be used depending, amongst other things, on the depth of penetration required; these include: air guns, 'sparkers', 'boomers', 'pingers' and 'chirp sonar'[121]. The main sound-producing elements used in oil exploration are air-gun arrays, which are towed from marine vessels[122]. Air guns release a volume of air under high pressure, creating a sound wave from the expansion and contraction of the released air bubble[123]. To yield high acoustic intensities, multiple air guns (typically 12 to 48) are fired with precise timing to produce a coherent pulse of sound. During a survey, guns are fired at regular intervals (e.g., every 10 to 15 seconds), as the towing source vessel moves ahead. Seismic air guns generate low frequency sound pulses below 250 Hz with the strongest energy in the range 10-120 Hz and peak energy between 30 to 50 Hz. Air guns

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113 Madsen, P.T., Wahlberg, M., Tougaard, J., Lucke, K. and Tyack, P. (2006). Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar. Ecol. Progr. Ser. 309, 279-295

114 Thomsen, F., Lüdemann, K., Kafemann, R. and Piper, W. (2006). Effects of offshore wind farm noise on marine mammals and fish, COWRIE Ltd, Newbury, U.K.

115 Nedwell, J.R. Parvin, S.J., Edwards, B., Workman, R., Brooker, A.G. and Kynoch, J.2010. Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters. Report for COWRIE, Newbury, UK

116 Wahlberg M, Westerberg H (2005) Hearing in fish and their reactions to sounds from offshore wind farms. Mar Ecol Prog Ser 288:295-309

117 Parvin, S. J., R. Workman, P. Bourke, and J. R. Nedwell. 2005. Assessment of tidal current turbine noise at Lybmouth site and predicted impact of underwater noise in Strangford Lough

118 OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

119 Schmidt V (2004) Seismic contractors realign equipment for industry's needs. Offshore 64:36–44

120 Tolstoy M, Diebold JB, Webb SC, Bohnenstiehl DR, Chapp E, Holmes RC, Rawson M (2004) Broadband calibration of R/V Ewing seismic sources. Geophys Res Lett 31:L14310

121 OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

122 Dragoset W (2000) Introduction to air guns and air-gun arrays. Geophys Lead Edge Explor 19:892–897

123 Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

also release low amplitude high-frequency sound, and acoustic energy has been measured up to 100 kHz[124]. The low frequency energy (10 to 120 Hz) is mainly focused vertically downwards, but higher frequency components are also radiated in horizontal directions.

The power of air-gun arrays has generally increased during the past decades, as exploration has moved into deeper waters. The nominal source level of an air-gun array can reach up to 260-262 dB (p-p) re 1 μPa @ 1m[125]. Sound signals from seismic air-gun surveys can be received thousands of kilometres away from the source if spread in a sound channel. Autonomous acoustic seafloor recording systems on the central mid-Atlantic Ridge showed year-round recordings of air-gun pulses from seismic surveys conducted more than 3000 km away[126]. Low-frequency energy can also travel long distances through bottom sediments, re-entering the water far from the source[127].

Sparkers and boomers are high-frequency devices that are generally used to determine shallow features in sediments. These devices may also be towed behind a survey vessel, with their signals penetrating several hundred (sparker) or tens (boomer) of metres of sediments due to their relatively higher frequency spectrum and lower transmitted power. Typical source levels can be 204 - 210 dB (rms) re 1 μPa @ 1 m[128]. Chirp sonars also produce sound in the upper frequency range of seismic devices (approx. 0.5 to 12 kHz). The peak source level for these devices is about 210 – 230 dB re 1 μPa @ 1 m[129].

SONAR

The use of acoustic energy for locating and surveying is described as active sonar. Sonar was the first anthropogenic sound to be deliberately introduced into the oceans on a wide scale. There are a variety of types of sonars that are used for both civilian and military purposes. They can occur across all sound frequencies and are divided in this section into low (<1 kHz), mid (1 to 10 kHz) and high frequency (>10 kHz). Military sonars use all frequencies while civilian sonar uses some mid but mostly high frequencies. Most types of sonar operate at one frequency of sound, but generate other unwanted frequencies (e.g., harmonics of the fundamental frequency due to non-linear processes). These extraneous lower intensity frequencies are rarely described but may have wider effects than the main frequency used, especially if they are at low frequencies which propagate further underwater[130].

Low-frequency sonar

Low-frequency active (LFA) sonars are used for broad-scale military surveillance, designed to provide the sound source over scales of hundreds of kilometres for other passive listening platforms to detect submarines[131]. Specialized support ships are used to deploy LFA sonars, which consist of arrays of source elements suspended vertically below the ship. The United States Navy's Surveillance Towed Array Sensor System (SURTASS) LFA sonar uses an array of up to 18 projectors operating in the frequency

[124] Goold, J.C. & Coates, R.F.W. 2006: Near Source, High Frequency Air-Gun Signatures. IWCSC/ 58/E30.

[125] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[126] Nieukirk, S.L., Stafford, K.M., Mellinger, D.K., Dziak, R.P. & Fox, C.G. 2004: Low-frequency whale and seismic airgun sounds recorded from the mid-Atlantic Ocean. – J. Acoust. Soc. Am., 115(4), 1832–184.

[127] McCauley, R.D., Hughes, J.R. 2006: Marine seismic mitigation measures – perspectives in 2006. IWC SC/58/E44. 10 pp.

[128] CCC/California Coastal Commission 2002: Consistency Determination. No. CD-14-02, USGS,2002 Southern California seismic survey. (In OSPAR 2009)

[129] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[130] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[131] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

range from 100 to 500 Hz, with a 215 dB re 1 μPa @ 1 m source level for each projector[132]. These systems are designed to project beams of energy in a horizontal direction, with a vertical beam width that can be steered above or below the horizontal. The effective source level of an LFA array can be 235 dB re 1 μPa @ 1 m or higher[133]. The signal includes both constant-frequency (CF) and frequency-modulated (FM) components with bandwidths of approximately 30 Hz[134]. A ping sequence can last 6 to 100 s, with a time between pings of 6 to 15 min and a typical duty cycle of 10%. Signal transmissions are emitted in patterned sequences that may last for days or weeks. In 2009 there were 2 LFA source ships, with a proposed expansion to 4 ships in 2011[135].

Mid-frequency sonar

Military mid-frequency sonars at high source levels are used for detecting submarines at moderate range (<10 km). There are about 300 mid-frequency sonars in active service in the world's navies[136] (Watts 2003). A US Navy hull-mounted system (AN/SQS-53C) sonar system uses pulses in the 2 – 10 kHz range (normally 3.5 kHz) and can operate at source levels of 235 dB re 1 μPa @ 1m. Another system (AN/SQS-56) uses this same frequency band but with lower source levels (223 dB re 1 μPa @ 1m)[137]. These systems were formerly used mainly in offshore waters, but now also scan shallower inshore environments to detect submarines that are able to operate closer to shore[138].

Some non-military sonars also operate in the mid-frequency band. Bathymetric sonars use these frequencies for wide-area, low resolution surveys. For example, the Fugro Seafloor survey model SYS09 uses both 9 and 10 kHz transducers operated at 230 dB re 1 μPa at 1m[139]. Sub-bottom profilers produce a mid-frequency (3 to 7 kHz) and high source level (230 dB re 1 μPa at 1 m) pulse, to map seafloor sediment layers and buried objects[140].

High-frequency sonar

Military high-frequency sonars are used in attacking or defending systems and are designed to work over hundreds of metres to a few kilometres[141]. These sonars use a wide range of modes, signal types and strengths. As with other military sonars, their usage is generally confined to exercise areas. Scanning sonars and synthetic aperture sonars are used for harbour defence, underwater search and recovery[142] and high intensity seabed mapping (side-scan sonar). Frequencies between 85 and 100 kHz are used for diver/swimmer detection while 100 kHz is optimal for obtaining a high resolution of seabed features

[132] Anonymous (2007) Final supplemental environmental impact statement for surveillance towed array sensor system low frequency active (SURTASS LFA) sonar, Vols 1 and 2. Department of the Navy, Chief of Naval Operations, Arlington, VA

[133] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy. Available at: www.nmfs.noaa.gov/prof_res/overview/Interim_BahamasReport.pdf

[134] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[135] DoN (Department of the Navy) (2009) Notice of intent to prepare a Supplemental Environmental Impact Statement/ Supplemental Overseas Environmental Impact Statement for employment of surveillance Towed Array Sensor System Low Frequency Acrive (SURTASS LFA) sonar. Federal Register 74(12):3574–3575 (microfiche) – in Hildebrand 2009

[136] Watts AJ (2003) Jane's underwater warfare systems, 15th edn. IHS Jane's, Berkshire, UK

[137] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy. Available at: www.nmfs.noaa.gov/prof_res/overview/Interim_BahamasReport.pdf

[138] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[139] Ibid

[140] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[141] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[142] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

including benthic cover. Hydroacoustic sonars are used to detect the presence of living organisms and particles in oceans, lakes, and rivers[143] (Simmonds & MacLennan 2005). By transmitting sound at high frequencies (20 to 1000 kHz), hydroacoustic sonars can detect individual objects or aggregates, such as schools of fish, in the water column[144].

Civilian and commercial sonars operating at high frequencies are used for detection, localization, and classification of various underwater targets (e.g., the seabed, plankton, fish, divers)[145]. These sonars generally produce sound at lower source levels with narrower beam patterns and shorter pulse lengths than military sonars, but are more widespread due to the large number of commercial and recreational vessels that are equipped with sonar[146]. Such vessels operate mostly in shallow shelf-seas and sonar usage occurs continuously throughout the year and at both day and night. Most of the systems focus sound downwards, though some horizontal fish finders are available. Fish finding sonars operate at frequencies typically between 24 and 200 kHz, which is within the hearing frequencies of some marine mammals, but above that of most fish[147] (Figure 2). Some horizontally-acting fish finding sonars are thought to be relatively powerful. For example, the Furuno FSV-24 sonar operates at 24 kHz and can detect and track shoals of tuna up to 5 km away[148]. Bathymetric mapping sonars use frequencies ranging from 12 kHz for deep-water systems to 70-100 kHz for shallow water mapping systems[149]. Multibeam sonars operate at high source levels (e.g., 245 dB re 1 μPa at 1 m) but have highly directional beams[150].

[143] Simmonds EJ, MacLennan DN (2005) Fisheries acoustics: theory and practice. Blackwell Publishing, London

[144] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[145] Ibid

[146] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[147] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[148] Ibid

[149] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[150] Ibid

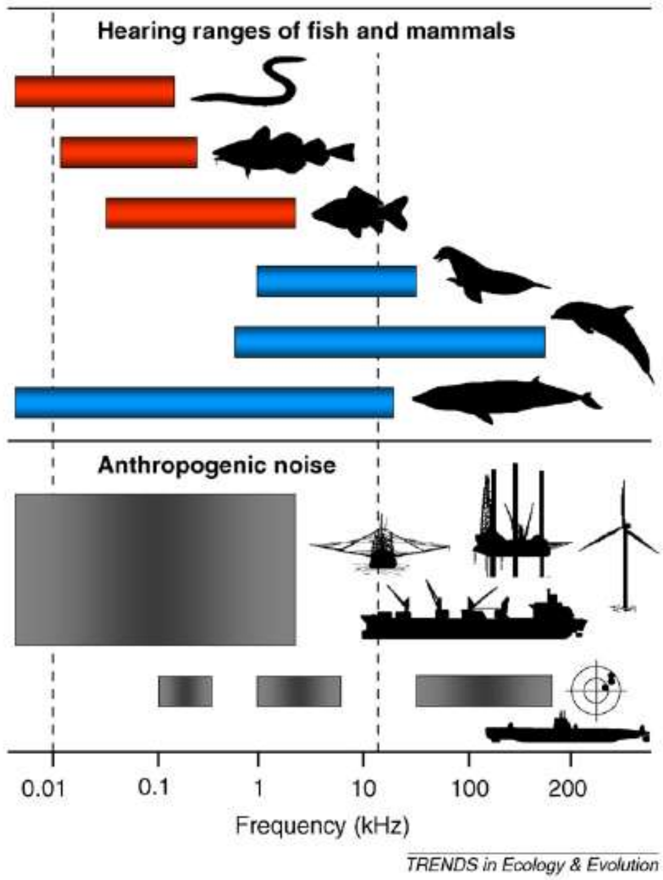

Figure 2. The main frequencies of anthropogenic noise sources and the hearing ranges of marine mammals and fish (from Slabbekorn et al., 2010)

SHIPS AND SMALLER VESSELS

Large commercial vessels

Large commercial vessels produce relatively loud and predominately low-frequency sounds. Source levels are generally in the 180 - 195 dB (re: 1µPa) range with peak levels in the 10 – 50 Hz frequency band[151] [152] [153]. The propulsion systems of large commercial ships are a dominant source of radiated underwater noise at frequencies <200 Hz[154]. Individual vessels produce unique acoustic signatures, although these signatures may change with ship speed, vessel load, operational mode and any implemented noise-reduction measures[155] [156].

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[151] Arveson, P. T. and D. J. Vendittis. 2000. Radiated noise characteristics of a modern cargo ship. Journal of the Acoustical Society of America 107, 118-129.

[152] Heitmeyer, R. M., S. C. Wales and L. A. Pflug. 2004. Shipping noise predictions: capabilities and limitations. Marine Technology Society Journal 37, 54-65.

[153] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[154] Ross D (1976) Mechanics of underwater noise. Pergamon Press, New York

[155] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[156] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

Most of the acoustic field surrounding large vessels is the result of propeller cavitation (when vacuum bubbles created by the motion of propellers collapse), causing ships at their service speed to emit low-frequency tonal sounds and (high-frequency) noise spectra up to tens of kHz quite close to vessels[157]. Smaller, but potentially significant, amounts of radiated noise can arise from on-board machinery (engine room and auxiliary equipment)[158]. Hydrodynamic flow over the ship's hull and hull attachments is an important broadband sound-generating mechanism, especially with increased ship speed[159]. There are also significant depth and aspect-related elements of radiated vessel sound fields as a function of shadowing and the Lloyd mirror effect near the surface of the water[160]. Source (propeller) depth is also important in terms of long-range propagation. Large vessels are loud near-field sources in both offshore (in shipping routes and corridors) and coastal waters (mainly in traffic lanes, waterways/canals or ports). Due to their loud and low-frequency signatures, large vessels dominate low-frequency background noise in many marine environments worldwide[161] [162].

Concerns of the acoustic impacts of noise from large vessel have focused mainly on marine animals that use low frequencies for hearing and communication (see Chapter 3). Modern cargo ships can also radiate sound at high frequencies, with source levels over 150 dB re 1μPa at 1m around 30 kHz[163]. Noise in these frequency bands has the potential to interfere (over relatively short ranges) with the communication signals of many marine mammals, including toothed whales not commonly thought of in terms of shipping noise masking[164].

Medium sized vessels

Tugboats, crewboats, supply ships, and many research vessels in the medium-sized category typically have large and complex propulsion systems, often including bow-thrusters[165]. Many fishing vessels also fall within this category. Typical broadband source levels for small to mid-size vessels are generally in the 165 - 180 dB (re: 1μPa) range[166] [167]. Most medium-sized ships are similar to large vessels in that most of the sound energy is low-frequency band (<1 kHz). While broadband source levels are usually slightly lower for medium-sized vessels than for the larger commercial vessels, there are some exceptions (e.g., as a function of age or maintenance of the ship), and medium-sized ships can produce sounds of sufficient

[157] Ibid

[158] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[159] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[160] Heitmeyer, R. M., S. C. Wales and L. A. Pflug. 2004. Shipping noise predictions: capabilities and limitations. Marine Technology Society Journal 37, 54-65.

[161] Wenz, G. M. 1962. Acoustic ambient noise in the ocean: spectra and sources. Journal of the Acoustical Society of America 34, 1936-1956.

[162] Greene, J., C. R. and S. E. Moore. 1995. Man-made Noise. Pp. 101-158. In J. W. Richardson, J. Greene, C.R., C. I. Malme and D. H. Thomson (eds.), Marine Mammals and Noise (Academic Press, New York).

[163] Arveson, P. T. and D. J. Vendittis. 2000. Radiated noise characteristics of a modern cargo ship. Journal of the Acoustical Society of America 107, 118-129.

[164] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[165] Ibid

[166] Kipple B, Gabriele C (2004) Glacier Bay watercraft noise— noise characterization for tour, charter, private, and government vessels. Technical Report NSWCCDE-71-TR- 2004/545, prepared for Glacier Bay National Park and Preserve, Naval Surface Warfare Center, Bremerton, WA

[167] Heitmeyer, R. M., S. C. Wales and L. A. Pflug. 2004. Shipping noise predictions: capabilities and limitations. Marine Technology Society Journal 37, 54-65.

level and frequency to contribute to marine ambient noise in some areas[168]. Mid-sized vessels spend most of their operational time in coastal or continental shelf waters, and overlap in time and space with marine animals, many of which prefer these waters for important activities such as breeding or feeding.

Small vessels

Small boats with outboard or inboard engines produce sound that is generally highest in the mid-frequency (1 to 5 kHz) range and at moderate (150 to 180 dB re 1 μPa @ 1 m) source levels although the output characteristics can be highly dependent on speed[169 170 171]. Source spectra for small craft and boats include tonal harmonics at the resonant vibrational frequencies of propeller blades, engines, or gearboxes below about 1 kHz, as well as significant energy resulting from propeller cavitation extending up to and above 10 kHz. Due to the generally higher acoustic frequency and near-shore operation, noise from smaller vessels is regarded as having more geographically-limited environmental impacts. Small craft and boats are of less concern in terms of overall increases in low-frequency marine ambient noise from so-called 'distant shipping', but can dominate some coastal acoustic environments, particularly partially-enclosed bays, harbours and/or estuaries[172.] In fact, recreational vessels have been identified as the most important contributor to mid-frequency ambient noise in some coastal habitats[173]. Small vessels are also becoming faster and more common in inshore and coastal waters. When small vessel traffic spatially or temporally overlaps with marine animal distributions, particularly during sensitive life history stages, acoustic impacts from small craft may have a significant impact on populations.

ACOUSTIC DETERRENT AND HARRASSMENT DEVICES

Acoustic Harassment Devices (AHDs) have been defined as high power devices operating at broadband source levels above 185 dB re 1μPa @1m while those operating at a lower source level are termed Acoustic Deterrent Devices (ADDs)[174]. ADDs or "pingers" are generally used to deter small cetaceans from bottom-set gillnets or other fisheries in order to reduce bycatch and incidental mortality. Pingers operate at much lower source levels than AHDs; usually 130 to 150 dB re 1 μPa[175]. Acoustic characteristics of ADDs differ particularly with respect to randomisation of pulse intervals and pulse duration. However, the signal structure and source levels of pingers can be relatively consistent when they have to comply with national or regional guidelines (e.g., EU Council regulation (EC) No 812/2004). Devices falling under this regulation are known to produce either 10 kHz tones or wide-band sweeps covering a frequency range from 20 to 160 kHz. Such pingers that are based on analogue signal generation emit tones (10 kHz) at source levels (broadband) between 130 and 150 dB re 1 μPa while

[168] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[169] Erbe C (2002) Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca)*, based on an acoustic impact model. Mar Mamm Sci 18:394–418

[170] Kipple B, Gabriele C (2004) Glacier Bay watercraft noise— noise characterization for tour, charter, private, and government vessels. Technical Report NSWCCDE-71-TR- 2004/545, prepared for Glacier Bay National Park and Preserve, Naval Surface Warfare Center, Bremerton, WA

[171] Jensen, F.H., et al., 2009. Vessel noise effects on delphinid communication. Mar Ecol Prog Ser 395:161-175

[172] Kipple B, Gabriele C (2003) Glacier Bay watercraft noise. Technical Report NSWCCDE-71-TR-2003/522, prepared for Glacier Bay National Park and Preserve, Naval Surface Warfare Center, Bremerton, WA

[173] Haviland-Howell G, Frankel AS, Powell CM, Bocconcelli A, Herman RL, Sayigh LS (2007) Recreational boating traffic: a chronic source of anthropogenic noise in the Wilmington, North Carolina Intracoastal Waterway. J Acoust Soc Am 122:151–160

[174] Reeves, R. R., R. J. Hofman, G. K. Silber, and D. Wilkinson. 1996. Acoustic deterrence of harmful marine mammal-fishery interactions: proceedings of a workshop held in Seattle Washington, 20- 22 March 1996. US Dept. Commer.

[175] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

digital devices can either have the same specifications or produce wideband sweeps at broadband source levels of 145 dB 1 μPa[176].

Acoustic Harassment Devices (AHDs) were originally developed to prevent pinniped predation on finfish farms, fisheries or salmon runs through the production of high source level acoustic signals. AHDs emit tone pulses or pulsed frequency sweeps at high source levels and there are a wide range of AHD specifications[177] [178]. A common feature of most AHDs is that they produce substantial energy in the ultrasonic range in addition to the main frequency band. The broadband source level of most AHDs is approximately 195 dB re 1 μPa. Due to their relatively high source level and often broadband characteristics AHDs can potentially be a significant source of noise in areas of dense fish farming[179].

Fish deterrent devices (FDDs) are mainly used in coastal or riverine habitats to temporarily displace fish from areas of potential harm (e.g., guiding fish away from water intakes of power plants)[180]. There is considerable variation between devices in terms of the frequency range which depends on the fish species to be targeted. If the device needs to be effective against a broad range of species, relatively low or infrasonic frequencies are generally used. For example, some devices produce infrasound at frequencies of about 10 Hz[181] or between 20 and 600 Hz[182]. Other devices produce primarily ultrasonic frequencies and are specifically designed to deter high-frequency hearing specialists. FDDs for some clupeid species which have ultrasonic hearing operate at frequencies between 120 kHz and 130 kHz, with source levels up to 190 dB[183]. FDDs generally produce sequences of short pulses (e.g., 100 - 1000 ms) at intervals of one to several seconds and duty cycles up to 50%[184].

OTHER ANTHROPOGENIC SOURCES

Research sound

Ocean science studies use a variety of different sound sources to investigate the physical structure of the ocean. Ocean tomography studies measure the physical properties of the ocean using sound sources with frequencies between 50 and 200 Hz and high source levels (165 - 220 dB re 1 μPa). The "Heard Island Feasibility Test" projected signals with centre frequencies of 57 Hz in the 'SOFAR channel' (175 m depth) at source levels up to 220 re 1 μPa[185]. The signals could be detected across ocean basins with received levels up to 160 dB re 1 μPa at 1 km distance. The experiment was thought to alter the

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[176] Ibid

[177] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115 (Table 2)

[178] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission (Table 8.1)

[179] Johnston, D. W., and T. Woodley. 1997. A survey of Acoustic Harrassment Device (AHD) Use at Salmon Aquaculture Sites in The Bay of Fundy , New Brunswick, Canada. Aquatic Mammals 24:51-61.

[180] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[181] Knudsen, F. R., P. S. Enger, and O. Sand. 1994. Avoidance responses to low frequency sound in downstream migrating atlantic aalmon smolt, Salmo salar. Journal of Fish Biology 45:227-233.

[182] Maes, J., A. W. H. Turnpenny, D. R. Lambert, J. R. Nedwell, Parmentier, and F. Ollevier. 2004. Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. Journal of Fish Biology 64:938-946

[183] Ross, Q. E., D. J. Dunning, J. K. Menezes, M. J. Kenna Jr., and G. Tiller. 1996. Reducing Impingement of Alewives with High Frequency Sound at a Power Plant on Lake Ontario. American Journal of Fisheries Management 16:548–559.

[184] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[185] Bowles, A. E., M. Smulrea, B. Wursig, D. P. DeMaster, and D. Palka. 1994. Relative abundance and behaviour of marine mammals exposed to transmissions from the Heard Island Feasibility Test. Journal of the Acoustical Society of America 96: 2469-2484.

distribution and vocalisation of some cetaceans but this could not be confirmed statistically due to a small sample size[186].

Another ocean-wide experiment was the "Acoustic Thermometry of Ocean Climate" (ATOC) research programme was initiated in the early 1990s to study ocean warming across the North Pacific basin[187]. The ATOC sound source emitted coded signals at four hour intervals at source levels of 195 dB re 1 µPa for up to 20 min with a 5 minute ramp-up period[188].The research programme received considerable attention from regulatory agencies, the public, and the scientific community because of concerns about the potential impact of the sound source on marine mammals[189]. The long time frame for operation of this experiment was a key aspect that led to concerns regarding its potential impact on marine mammals[190] [191].

Research projects also use sound to estimate current speed and direction by using drifting sources called SOFAR floats[192]. These devices drift at depth and periodically emit a high-intensity tone (195 dB re 1 µPa at 1 m) between 185 and 310 Hz. The sounds are detected by distant receivers and their timing is used to determine the float location and therefore its drift, as a proxy for deep currents[193].

Icebreakers

Ice-breaking ships are a source of noise in Polar Regions[194]. Two types of noise have been identified during ice breaking: bubbler system noise and propeller cavitation noise[195]. Some ships are equipped with bubbler systems that blow high-pressure air into the water around the ship to push floating ice away. The noise is continuous while the bubbler system is operating, with a broadband spectrum below 5 kHz. A source level of 192 dB re 1 µPa at 1 m has been reported for bubbler system noise. Icebreaker propeller cavitation noise occurs when the ship rams the ice with its propeller turning at high speed. The spectrum of propeller cavitation noise is broadband up to at least 20 kHz, and has a source level of 197 dB re 1 µPa at 1 m[196].

Acoustic telemetry

Acoustic telemetry is used for underwater communications, remote vehicle command and control, diver communications, underwater monitoring and data logging, trawl net monitoring and other industrial and

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186 Ibid

187 Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

188 HOWE, B. M. 1996. Acoustic Thermometry Of Ocean Climate (ATOC): Pioneer Seamount Source Installation. U.S. Government Technical Memo. Report Number A346903. 84 PP.

189 NRC 2000. Marine mammals and low-frequency sound: progress since 1994. Committee to Review Results of ATOC's Marine Mammal Research Program, Ocean Studies Board, National Research Council. 160 pp.

190 Herman 1994. Hawaiian Humpback Whales and ATOC: A Conflict of Interests. The Journal of Environment Development. 3: 263-76

191 Potter, JR. 1994. ATOC: Sound Policy or Enviro-Vandalism? Aspects of a modern media-fueled policy issue. The Journal of Environment Development. 3: 47-62

192 Rossby, T., Price, J. and Webb, D.. 1986. The spatial and temporal evolution of a cluster of SOFAR floats in the POLYMODE local dynamics experiment (LDE). Journal of Physical Oceanography 16: 428-442.

193 Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

194 Erbe, C and Farmer, D.M. 2000. Zones of impact around icebreakers affecting Beluga whales in the Beaufort Sea. J. Acoust. Soc. Am. 108

195 Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

196 Ibid

research applications requiring underwater wireless communications[197]. For seafloor monitoring, acoustic modems are used as an interface for subsurface data transmissions, sending data using modulated acoustic signals between seafloor instruments and surface buoys. Long-range systems can operate over distances of up to 10 km using frequencies of 7 to 45 kHz, at source levels of up to 190 dB re 1 μPa @ 1 m. A relatively new integrated communications project is the "Acoustic Communication Network for Monitoring of Underwater Environment in Coastal Areas (ACME)". This system uses chirps of continuously varying frequencies and frequency-shift keying noise covering a frequency range of 5 - 15 kHz[198].

[197] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[198] Kastelein, R. A., W. C. Verboom, M. Muijsers, N. V. Jennings, and S. van der Heul. 2005. The influence of acoustic emissions for underwater data transmission on the behaviour of harbour porpoises (*Phocoena phocoena*) in a floating pen. Marine Environmental Research 59:287-307.

III. SYNTHESIS OF SCIENTIFIC INFORMATION ON KNOWN AND POTENTIAL IMPACTS OF UNDERWATER NOISE

Underwater sound is an extremely important constituent of the marine environment and plays an integral part of the lives of most marine vertebrates[199] and also many invertebrates[200] [201]. This chapter provides a synthesis of current scientific information and thinking concerning the impacts of anthropogenic sound on marine life. Most of the information available is concerned with the effects of sound and noise on marine mammals, particularly cetaceans. Considerably less research has been completed for marine fish, other vertebrates (e.g., marine turtles) and particularly marine invertebrates.

Anthropogenic underwater noise is known to have a variety of impacts on marine species, ranging from exposures that cause no adverse impacts, to significant behavioural disturbances, to hearing loss, physical injury and mortality (Annex 1). The potential effects depend on a number of factors, including the duration, nature and frequency content of the sound, the received level (sound level at the animal), the overlap in space and time with the organism and sound source, and the context of exposure (i.e., animals may be more sensitive to sound during critical times, like feeding, breeding/spawning/, or nursing/rearing young)[202]. Adverse impacts can be broadly divided into three categories: masking, behavioural disturbance and physiological changes (hearing loss, discomfort, injury)[203] although there is some overlap between these categories. In extreme cases, where there are very high received sound pressure levels often close to the source, the intense sounds can lead to death. There have been a number of extensive reviews of the impacts of anthropogenic sound on marine organisms during the last two decades[204] [205] [206] [207] [208] [209] [210] [211] [212] [213] [214]. In addition, the potential for further more subtle biological effects (e.g.,

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[199] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

[200] Montgomery, J.C., Jeffs, A., Simpson, S.D., Meekan, M., Tindle, C., 2006. Sound as an orientation cue for the pelagic larvae of reef fishes and decapod crustaceans. Adv. Mar. Biol. 51, 143–196.

[201] Simpson SD, Radford AN, Tickle EJ, Meekan MG, Jeffs AG (2011) Adaptive Avoidance of Reef Noise. PLoS ONE 6(2): e16625. doi:10.1371/ journal.pone.0016625

[202] Tasker, M.L, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

[203] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[204] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[205] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[206] NRC (2005) Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects. National Research Council of the National Academies of Science, Washington, DC.

[207] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[208] Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R. Jr., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A. and Tyack, P.L. 2007. Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals, 33: 411 – 521.

[209] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[210] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

physiological, developmental, cellular and genetic responses) of anthropogenic noise on mainly terrestrial animals has been suggested[215] and should be taken into consideration for the marine environment. The chronic and cumulative effects of anthropogenic noise exposure on marine species and populations also require attention[216].

This chapter will summarise current scientific knowledge and thinking on the observed and potential effects of anthropogenic noise on marine biodiversity and is divided into three main sections comprised of marine mammals, marine fish and other fauna such as further vertebrate taxa and invertebrates.

IMPACTS ON MARINE MAMMALS

The theoretical zones of underwater noise influence on marine mammals have been defined and are mainly based on the distance between the source of the sound and the receiver[217] (Figure 3).

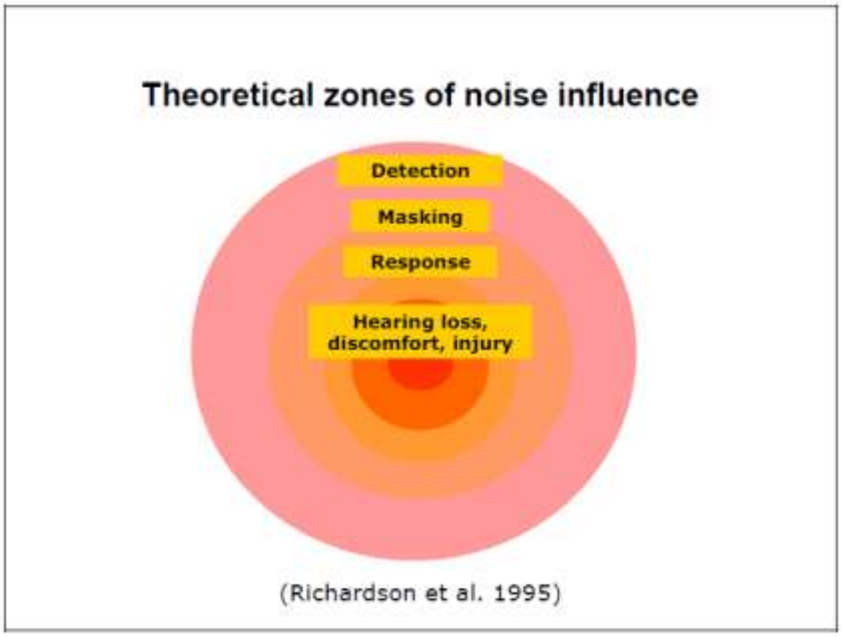

Figure 3. Theoretical zones of noise influence (after Richardson et al. 1995)

This model has been used extensively for impact assessments where the zones of noise influence are determined, based on a combination of sound propagation modelling or sound pressure level measurements and information on the hearing capabilities of marine species. However, the model gives

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211 Popper, A.N., and Hastings, M.C. 2009b. The effects of human-generated sound on fish. Integrative Zoology, 4: 43 – 52.

212 OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

213 Ibid

214 André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

215 Kight, C.R. and Swaddle, J.P. 2011. How and why environmental noise impacts animals: an integrative, mechanistic review. Ecology Letters doi: 10.1111/j.1461-0248.2011.01664.x

216 Wright, J.W., Deak, T. and Parsons, E.C.M. 2009. Concerns Related to Chronic Stress in Marine Mammals. IWC SC/61/E16 7 pp.

217 Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

only a very rough estimate of the zones of influence as sound in the marine environment is always three-dimensional. Interference, reflection and refraction patterns within sound propagation will also lead to considerably more complex sound fields than those based on the above model. This complexity may result in particular effects such as an increase in received sound energy with distance, especially when multiple sound sources are used simultaneously, for example during seismic surveys[218].

A INJURY AND PHYSICAL EFFECTS

Marine mammals are known to be susceptible to a range of physiological effects and injuries that have been attributed to sources of anthropogenic sound (Annex 1). The most striking evidence of serious injury to marine mammals has been accumulated in the last decade and is concerned with the impact of naval sonar on cetaceans, particularly deep diving beaked whales of the genera *Ziphius* and *Mesopolodon*, and the occurrence of mass stranding events[219] [220]. Atypical mass stranding events of mainly beaked whales first began to be reported in the mid 1980's and usually coincided with the use of mid-frequency active sonar by the military[221] [222] [223]. Necropsies of beaked whales stranded in the Bahamas in 2000 clearly revealed that the animals had suffered acoustic trauma resulting in haemorrhaging around the brain, in the inner ears and in the acoustic fats (fats located in the head which are involved in sound transmission)[224]. The official interim report for the mass stranding event concluded that an acoustic or impulse injury caused the animals to strand and that mid-frequency active sonar used by the navy while transiting was the most plausible source of the acoustic trauma or impulse[225]. Analysis of subsequent mass stranded beaked whales found acute systemic micro-haemorrhages and gas and fat emboli in individuals that mass-stranded during a naval exercise in the Canary Islands in 2002[226] [227]. Similarly, four species of stranded cetacean (one beaked whale, two dolphin and one porpoise species) had acute and chronic lesions in liver, kidney and lymphoid tissue (lymph nodes and spleen) associated with intravascular gas bubbles (emboli)[228]. The mechanism for gas bubble generation (gas bubble disease) in supersaturated tissue of

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[218] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[219] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy.

[220] Fernández, A., Edwards, J.F., Rodríguez, F., Espinosa de los Monteros, A., Herráez, P., Castro, P., Jaber, J.R., Martín, V., and Arbelo, M. 2005. 'Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57.

[221] Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J. Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernández, A. Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J., Lowry, L. and Benner, L. 2006. Understanding the impacts of anthropogenic sound on beaked whales? Journal of Cetacean Research and Management 7: 177–187.

[222] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[223] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[224] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy.

[225] Ibid

[226] Jepson, P. D., Arbelo, M., Deaville, R., Patterson, I. A. P., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herraez, P., Pocknell, A. M., Rodriguez, F., Howie, F. E., Espinosa, A., Reid, R. J., Jaber, J. R., Martin, V., Cunningham, A. A. and Fernández A. 2003. Gas-bubble lesions in stranded cetaceans. Nature 425: 575–576.

[227] Fernández, A., Edwards, J.F., Rodríguez, F., Espinosa de los Monteros, A., Herráez, P., Castro, P., Jaber, J.R., Martín, V., and Arbelo, M. 2005. 'Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57.

[228] Jepson, P. D., Deaville, R., Patterson, I. A. P., Pocknell, A. M., Ross, H. M., Baker, J. R., Howie, F. E., Reid, R. J., Colloff, A. and Cunningham, A. A. 2005. Acute and chronic gas bubble lesions in cetaceans stranded in the United Kingdom. Veterinary Pathology 42: 491–305.

diving marine mammals (that leads to symptoms similar to decompression sickness (DCS) in humans) is thought to be an adverse behavioural response to exposure to noise[229], or a direct physical effect of sound energy on gas bubble precursors in the animal's body[230] (see Figure 4). In the case of beaked whales, if individuals change behaviour to a series of shallower dives with slow ascent rates and shorter stays on the surface they could experience excessive nitrogen tissue supersaturation driving potentially damaging bubble formation in tissues[231]. However, this is currently a working hypothesis and requires testing through a specific programme of research[232]. Beaked whales are also thought to be more acoustically sensitive to active sonar than other species. A comparison of the effect of mid-frequency sonar on Blainville's beaked whale and three other non-beaked species (pilot whale, false killer whale, melon headed whale) showed that the responses of the beaked whales were stronger between affected individuals and controls than in the other species[233].

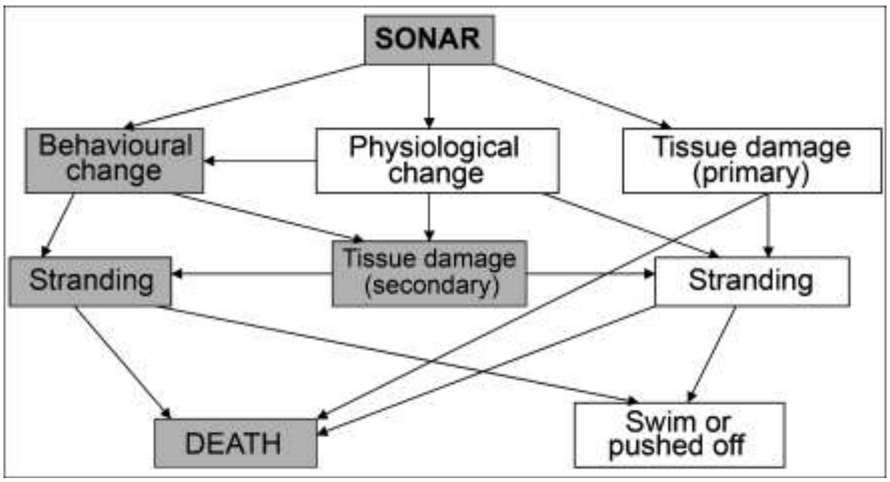

Figure 4. Potential mechanistic pathways by which beaked whales are affected by active sonar. (See Cox et al., 2006 for detailed discussion)

Further mass stranding events of beaked whales and other cetaceans have been reported in a range of locations around the world.[234] [235] [236]. Research for Cuvier's beaked whale indicates that there have been 40 mass stranding events of two or more individuals since 1960 and 28 of these events occurred at the

[229] Cox, T. M., et al. 2006. Understanding the impacts of anthropogenic sound on beaked whales? Journal of Cetacean Research and Management 7: 177–187.

[230] Crum, L.A., Bailey, M.R., Guan, J., Hilmo, P R., Kargl, S.G., Matula, T.J. & Sapozhnikov, O.A. (2005) Monitoring bubble growth in supersaturated blood and tissue ex vivo and the relevance to marine mammal bioeffects. Acoustics Research Letters Online. DOI: 10.1121/1.1930987

[231] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[232] Cox, T. M., et al. 2006. Understanding the impacts of anthropogenic sound on beaked whales? Journal of Cetacean Research and Management 7: 177–187.

[233] Cited from OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[234] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission (Table 6.1)

[235] Wang, J.W. and Yang, S-C. 2006. Unusual stranding events of Taiwan in 2004 and 2005. J. Cetacean Res. Manage. 8(3): 283–292

[236] Dolman SJ, Pinna E, Reid RJ, Barleya JP, Deaville R, Jepson PD, O'Connell M, Berrow S, Penrose RS, Stevick PT, Calderan S, Robinson KP, Brownell Jr RA and Simmonds MP (2010) A note on the unprecedented strandings of 56 deep-diving whales along the UK and Irish coast. Marine Biodiversity Records (2010), 3: e16

same time and place as naval manoeuvres or the use of active sonar or near naval bases[237]. A number of other (non-beaked) species such as minke whales and pygmy sperm whales have stranded concurrently with beaked whales in sonar-related stranding events, while other species including long-finned pilot whales, melon headed whales, dwarf sperm whales and harbour porpoises, have stranded in noise-related events[238]. The fact that deep diving cetaceans other than beaked whales have shown to have gas embolism disease in stranded animals suggests that sonar or other noise impacts may be more widespread than previously thought[239]. Additionally mortality may be under-estimated if based solely on stranded individuals as affected cetaceans are also highly likely to die at sea[240] and not be washed up or detected which is likely to be related to local environmental conditions[241].

There is little evidence of other sources of anthropogenic underwater noise causing direct physical damage to marine mammals. There are a few poorly documented cases of injury (organ damage and rupture of gas filled cavities such as lungs, sinuses and ears), and deaths of marine mammals have been caused by the use of explosives[242]. A dramatic pressure drop, such as occurs from blast waves, may cause air-filled organs to rupture[243]. The death of two humpback whales was attributed to acoustic trauma caused by a 5000 kg explosion through severe injury to the temporal bones[244]. There is no documented case of injury caused by pile driving for marine mammals at sea although experimental studies in captivity using simulated source levels[245] [246] suggest that the levels of intense sound produced during pile driving are strong enough to cause noise induced hearing loss in some species. Hearing losses are classified as either temporary threshold shifts (TTS) or permanent threshold shifts (PTS), where threshold shift refers to the raising of the minimum sound level needed for audibility[247]. Repeated TTS is thought to lead to PTS. Hearing losses can reduce the range for communication, interfere with foraging capacity, increase vulnerability to predators, and may cause erratic behaviour with respect to migration, mating, and stranding[248]. Current research indicates that sound from pile driving has the potential to induce hearing loss in marine mammals if they remain within a certain distance of the source which has been estimated between 100 and 500 metres for PTS[249] [250]. However the most severe acoustic impacts recorded

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[237] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[238] Ibid

[239] Ibid

[240] International Whaling Commission Scientific Committee (IWC/SC). 2005. Report and Annex K of the 2005 Scientific Committee Report: Report of the Standing Working Group on Environmental Concerns. J. Cetacean Res. Manag. 7 (Suppl.): 267-305

[241] Faerber, M.M and Baird, R.W. 2010. Does a lack of observed beaked whale strandings in military exercise areas mean no impacts have occurred? A comparison of stranding and detection probabilities in the Canary and main Hawaiian Islands. Marine Mammal Science. DOI: 10.1111/j.1748-7692.2010.00370.x

[242] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[243] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

[244] Ketten, D.R. (1995). Estimates of blast injury and acoustic zones fro marine mammals from underwater explosions. In: Kastelein, R.A., Thomas, J.A., and Nachtigall, P.E. (ed), Sensory Systems of Aquatic Mammals. De Spil Publishers, Woerden, NL, pp: 391-407.

[245] Mooney, T.A., Nachtigall, P.E., Breese, M., Vlachos, S. & Au, W.L. (2009) Predicting temporary threshold shifts in a bottlenose dolphin (*Tursiops truncatus*): the effects of noise level and duration J. Acoust. Soc. Am. 125(3): 1816-1826.

[246] Kastak, D., Southall, B. L., Schusterman, R. J. & Kastak, C. R. (2005) Underwater temporary threshold shift in pinnipeds: effects of noise level and duration. Journal of the Acoustical Society of America 118: 3154-3163.

[247] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

[248] Ibid

[249] Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. & Thompson, P. (2010) Assessing underwater noise levels during pile-driving at an offshore wind farm and its potential effects on marine mammals. Marine Pollution Bulletin 60: 888-897.

on cetaceans to date (active sonar) were due to exposures thought too low to induce TTS, according to current predictive models[251]. Hearing damage in marine mammals from shipping noise has not been reported and is thought to be unlikely to occur from the passage of a single vessel[252]. However there is the potential for permanent damage to hearing from sustained and/or repeated exposure to shipping noise over long periods[253].

B MASKING

The term masking refers to when increased levels of background or ambient noise reduces an animal's ability to detect relevant sound[254] such as important acoustic signals for communication, echolocation or of the marine environment for marine mammals. If the anthropogenic noise is strong enough relative to the received signal then the signal will be 'masked'[255]. If features within the signal convey information, it may be important to receive the full signal with an adequate signal-to-noise ratio to recognize the signal and identify the essential features[256]. As ambient noise or transmission range increases, information will be lost at the receiver, ranging from subtle features to complete failure to detect the signal[257]. Consequently, the active space in which animals are able to detect the signal of a conspecific[258] or other acoustic cue will decrease with increased masking noise.

Masking in the marine environment is a regarded as a key concern for marine mammals, especially for those that communicate using low frequencies such as baleen whales, seals and sea lions and also some of the of vocalisations of toothed whales[259] (Figure 5). The principal constituent of low–frequency (5–500 Hz) ambient noise levels in the world's oceans are acoustic emissions from commercial shipping[260]. Masking can also occur at higher frequencies (1–25 kHz) when vessels are in close proximity to an animal and exposed to cavitation noise from propellers. More localised masking in the coastal and inshore zone is a growing cause for concern as the number and speed of smaller motorised vessels increase dramatically in many regions[261].

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[250] De Jong, C.A.F. & Ainslie, M.A. (2008) Underwater radiated noise due to the piling for the Q7 Offshore Wind Park. Acoustics 2008 Conference (ASA-EAA), Paris, 29 June – 4 July, abstracts: 117-122.

[251] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[252] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[253] Ibid

[254] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

[255] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[256] Brumm H, Slabbekoorn H (2005) Acoustic communication in noise. Adv Stud Behav 35:151–209

[257] Gelfand SA (2004) Hearing - an introduction to psychological and physiological acoustics. Marcel Dekker, New York.

[258] Marten K, Marler P (1977) Sound transmission and its significance for animal vocalization. Behav Ecol Sociobiol 2: 271–290

[259] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[260] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

[261] Jensen, F.H., Bedjer. L., Wahlberg, M., Aguilar Soto, N., Johnson, M., Madsen, P.T. 2009. Vessel noise effects on delphinid communication. Mar. Ecol. Prog. Ser. 395: 161-175.

Figure 5. Typical frequency sound bands produced by marine mammals (and fish) compared with the nominal low-frequency sounds associated with commercial shipping (after OSPAR 2009)

There have been numerous studies of the effects of masking from vessel noise on marine mammals including baleen whales[262], belugas[263], bottlenose dolphins[264 265 266], short-finned pilot whales[267] and killer whales[268 269]. Some of these have estimated or modelled the extent to which low-frequency noise from shipping or other vessels can dramatically reduce communication ranges for marine animals[270 271]. For example, the noise of an icebreaker vessel was predicted to mask beluga calls up to 40 km from the vessel[272] while pilot whales in deep water habitat could suffer a 58% reduction in communication range caused by the masking effect of small vessels in the coastal zone[273]. Using a metric to measure ‘communication masking’ the acoustic communication space for the highly endangered north Atlantic

[262] Payne, R. and D. Webb. 1971. Orientation by means of long range acoustic signaling in baleen whales. Annals of the New York Academy of Sciences 188, 110-141.

[263] Erbe, C. and D. M. Farmer. 1998. Masked hearing thresholds of a beluga whale (*Delphinapterus leucas*) in icebreaker noise. Deep Sea Research 45, 1373–1387.

[264] Buckstaff KC (2004) Effects of watercraft noise on the acoustic behaviour of bottlenose dolphins, *Tursiops truncatus*, in Sarasota Bay, Florida. Mar Mamm Sci 20:709–725

[265] Morisaka, T., M. Shinohara, F. Nakahara, and T. Akamatsu. 2005. Effects of ambient noise on the whistles of Indo-Pacific bottlenose dolphin populations. Journal of Mammalogy 86, 541-546.

[266] Jensen, F.H., Bedjer. L., Wahlberg, M., Aguilar Soto, N., Johnson, M., Madsen, P.T. 2009. Vessel noise effects on delphinid communication. Mar. Ecol. Prog. Ser. 395: 161-175

[267] Ibid

[268] Erbe, C. 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. Marine Mammal Science 18, 394- 418

[269] Foote AD, Osborne RW, Hoelzel AR (2004) Whale-call response to masking boat noise. Nature 428:910

[270] Southall, B. L., A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. Greene Jr., D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals 33, 411-521.

[271] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[272] Erbe, C. and D. M. Farmer. 2000. Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. Journal Acoustical Society of America 108, 1332-1340.

[273] Jensen, F.H., Bedjer. L., Wahlberg, M., Aguilar Soto, N., Johnson, M., Madsen, P.T. 2009. Vessel noise effects on delphinid communication. Mar. Ecol. Prog. Ser. 395: 161-175

right whale has shown to be seriously compromised by noise from commercial shipping traffic[274]. Increasing anthropogenic noise levels in the oceans therefore have the potential to significantly affect threatened populations of marine mammals. Masking effects on marine mammals have also been suggested for other anthropogenic noise sources including low-frequency sonar on Humpback whales[275] [276], pile driving sound on bottlenose dolphins[277] and low-frequency wind turbine noise on harbour seals and harbour porpoises[278] [279]. There is also the potential for certain Acoustic Harassment Devices to mask the communication signals of some species of Delphinid cetaceans or seals[280]. Low-frequency sounds produced by fish deterrent devices or tidal turbines have the potential to mask baleen whale communication or the vocalisations of some seal species[281].

There is increasing evidence that cetaceans are compensating for the masking effects of anthropogenic noise by changing the frequency, source level, redundancy, or timing of their signals[282] [283] [284] [285] [286] [287]. This phenomenon suggests that the anthropogenic noise levels in the marine environment such as vessel noise are clearly interfering with communication in marine mammals[288]. Temporary changes in signalling may enable animals to cope with different noise levels[289]. Changes in signal parameters may adequately compensate for small increases in masking noise and are not likely to have any adverse effects during short periods of time, but may not be sufficient to compensate for more severe levels of masking[290]. The

[274] Clark, C.W., Ellison, W.T., Southall, B.L., Hatch L., van Parijs, S.M., Frankel, A. and Ponirakis, D. 2009. Acoustic masking in marine ecosystems: intuitions, analyses, and implication. Marine Ecology Progress Series, 395: 201 – 222.

[275] Miller, P.J.O., Biassoni, N., Samuels, A. and Tyack, P.L. 2000. Whale songs lengthen in response to sonar. Nature, 405: 903

[276] Fristrup, K.M., Hatch, L.T. & Clark, C.W. (2003) Variation in humpack whale (*Megaptera novaengliae*) song length in relation to low-frequency sound broadcasts. *Journal of the Acoustical Society of America*, **113**, 3411–3424.

[277] David, J.A. 2006. Likely sensitivity of bottlenose dolphins to pile-driving noise. Water and Environment Journal. 20: 48–54

[278] Koschinski, S., Culik, B.M., Henriksen, O.D., Tregenza, N., Ellis, G., Jansen, C. & Kathe, G. (2003) Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2MWwindpower generator. Marine Ecology Progress Series, 265, 263–273.

[279] Lucke, K., Lepper, P.A., Hoeve, B., Everaarts, E., van Elk, N., and Siebert, U. (2007). Perception of low-frequency acoustic signals by a harbour porpoise (Phocoena phocoena) in the presence of simulated offshore wind turbine noise. Aquatic Mammals, 33: 55-68.

[280] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[281] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[282] Buckstaff KC (2004) Effects of watercraft noise on the acoustic behaviour of bottlenose dolphins, *Tursiops truncatus*, in Sarasota Bay, Florida. Mar Mamm Sci 20:709–725

[283] Lesage, V., Barrette, C., Kingsley, M.C.S., Sjare, B. 1999. The effect of vessel noise on the vocal behaviour of Belugas in the St Lawrence river estuary, Canada. Mar Mamm Sci 15: 65-84

[284] Foote AD, Osborne RW, Hoelzel AR (2004) Whale-call response to masking boat noise. Nature 428:910

[285] Morisaka, T., M. Shinohara, F. Nakahara, and T. Akamatsu. 2005. Effects of ambient noise on the whistles of Indo-Pacific bottlenose dolphin populations. Journal of Mammalogy 86, 541-546.

[286] Holt, M.M., Noren, D.P., Veirs, V., Emmons, C.K. and Veirs, S. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. J. Acoust. Soc. Am. 125. DOI: 10.1121/1.3040028

[287] Parks, S. E., C. W. Clark, and P. L. Tyack. 2007. Short- and longterm changes in right whale calling behavior: the potential effects of noise on acoustic communication. Journal of the Acoustical Society of America 122:3725–3731.

[288] Tyack, P.L. 2008. Implications for marine mammals of large-scale changes in the marine acoustic environment. Journal of Mammalogy. 89: 549-558

[289] Miksis-Olds JL, Tyack PL (2009) Manatee (*Trichechus manatus*) vocalization usage in relation to environmental noise levels. J Acoust Soc Am 125:1806–1815

[290] Wartzok D, Popper AN, Gordon JCD, Merrill J (2003) Factors affecting the responses of marine mammals to acoustic disturbance. Mar Technol Soc J 37:6–15

energetic and functional costs of making changes to vocalisations for individuals or populations are currently unknown[291].

C BEHAVIOURAL DISTURBANCE

A wide range of anthropogenic sound sources are known to elicit changes in behaviour in marine mammals[292 293] (Table 2) and the responses elicited can be complex. Behavioural responses may range from changes in surfacing rates and breathing patterns to active avoidance or escape from the region of highest sound levels. Responses may also be conditioned by certain factors such as auditory sensitivity, behavioural state (e.g., resting, feeding, migrating), nutritional or reproductive condition, habit or desensitization, age, sex, presence of young, proximity to exposure and distance from the coast[294 295]. Therefore, the extent of behavioural disturbance for any given acoustic signal can vary both within a population as well as within the same individual[296]. Since the first extensive review of marine mammals and anthropogenic noise was completed in the mid-nineties[297] there have been a number of further detailed appraisals that document how various sources of anthropogenic sound can affect marine mammal behaviour[298 299 300 301]. Many of the studies reporting behaviour up to this time were observational rather than experimental and often lacked proper controls.

The subjects of vocal plasticity and mass strandings have been covered previously in sections for masking and physiological effects of anthropogenic sound respectively. This section provides information on three broad areas of behavioural change in marine mammals: disturbance responses, interruption of normal activity and habitat displacement, and leads onto a discussion of potential population effects, physiological responses and chronic effects.

There is extensive information documenting the disturbance responses of marine mammals to anthropogenic sounds such as recreational boat noise, industrial maritime traffic activities, seismic surveys, oceanographic tests, sonar, acoustic hardware, airplanes and explosions[302 303]. Short term

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[291] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[292] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[293] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

[294] Richardson, W.J. & Würsig, B. 1997: Influences of man-made noise and other human actions on cetacean behaviour. Mar. Fresh. Behav. Physiol. 29: 183-209

[295] Bejder L., Samuels, A., Whitehead, H., Finn, H. and Allen, S. 2009. Impact assessment research use and misuse of habituation, sensitisation and tolerance in describing wildlife responses to anthropogenic stimuli. Marine Ecology Progress Series. 395: 177-185

[296] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[297] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[298] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[299] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[300] Tyack, P.L. 2008. Implications for marine mammals of large-scale changes in the marine acoustic environment. Journal of Mammalogy. 89: 549-558

[301] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

[302] Ibid (Table 6)

reactions to man-made sounds on cetaceans include sudden dives, fleeing from sound sources, vocal behavioural change, shorter surfacing intervals with increased respiration, attempts to protect the young, increased swim speed and abandonment of the polluted area[304]. For example, both killer whales and dolphins are known to change their motor behaviour in response to small vessel presence and noise[305] [306] while baleen whales such as blue and fin whales have similarly responded to shipping movements and noise[307]. Manatees have been shown to respond to approaching vessels by changing fluke rate, heading, and dive depth[308].Cessation of humpback singing was shown with transmissions of an experimental sound 200 km away[309]. The use of air-gun arrays during seismic surveys and their impact on marine mammal behaviour has been thoroughly assessed in terms of behavioural responses. A range of conclusions have been drawn with respect to behavioural reactions to seismic surveys, and there is currently a lack of a consensus in the scientific community on the occurrence, scale and significance of such effects[310]. However, many types of marine mammals have reacted strongly to the intense sound of seismic surveys. A number of species of baleen whale on the whole show avoidance behaviour[311] as do pinniped species[312] [313]. As assessment of cetacean responses to 201 seismic surveys resulted in the suggestion that odontocetes may adopt a strategy of moving out of the affected area entirely while slower moving mysticetes move away from the seismic survey to increase the distance from the source, but do not leave the area completely[314]. Observations of sperm whales that were resident in an area with seismic surveys occurring over many years did not record any avoidance behaviour, which may indicate habituation, but did see more subtle changes in foraging behaviour at sound levels that were considerably below the threshold level used to predict a disruption of behaviour[315]. These subtle changes were only picked up because of a rigorous experimental design. Long-term in-depth studies are also important to detect subtle effects. The apparent habituation of a dolphin population to vessel noise was actually a result of more sensitive individuals avoiding the affected area whilst the less sensitive ones remained[316].

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303 OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

304 André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

305 Nowacek, S. M., R. S. Wells and A. Solow. 2001. Short-term effects of boat traffic on bottlenose dolphins, *Tursiops truncatus*, in Sarasota Bay, Florida. Marine Mammal Science 17, 673-688

306 Williams, R., A. W. Trites and D. E. Bain. 2002. Behavioural responses of killer whales (*Orcinus orca*) to whale-watching boats: opportunistic observations and experimental approaches. Journal of Zoology London 256, 255-270

307 Edds, P.L. and Macfarlane, J.A.F. 1987. Occurrence and general behavior of balaenopterid cetaceans summering in the St Lawrence Estuary, Canada. Can. J. Zool. 65:1363-1376

308 Nowacek, S. M., R. S. Wells, E. C. G. Owen, T. R. Speakman, R. O. Flamm and D. P. Nowacek. 2004. Florida manatees, *Trichechus manatus latirostris*, respond to approaching vessels. Biological Conservation 119, 517-523

309 Risch D, Corkeron PJ, Ellison WT, and Van Parijs SM. 2012. Changes in humpback whale song occurrence in response to an acoustic source 200 km away. PLoS ONE 7(1): e29741. doi:10.1371/journal.pone.0029741

310 OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

311 Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

312 Thompson, D. (ed.) (2000): Behavioural and physiological responses of marine mammals to acoustic disturbance – BROMMAD. Final Scientific and Technical Report to European Commission. MAS2 C7940098

313 Bain, D.E. & Williams, R. 2006: Long-range effects of airgun noise on marine mammals: Responses as a function of received sound level and distance. IWC-SC/58E35

314 Stone, C.J. and Tasker, M.L. 2006. The effect of seismic airguns on cetaceans in UK waters. J. Cetacean Res. Manag. 8: 255-263

315 Miller P.J.O , Johnson, M.P., Madsen, P.T., Biassoni, N., Quero, M. and Tyack, P.L. 2009. Using at-sea experiments to study the effects of airguns on the foraging behaviour of sperm whales in the Gulf of Mexico. Deep-Sea Research I. doi:10.1016/j.dsr.2009.02.008

316 Bejder., L et al. 2006. Decline in relative abundance of bottlenose dolphins exposed to long-term disturbance. Conservation Biology Volume 20, No. 6, 1791–1798

It is thought that repeated short-term changes in behaviour may lead to long-term impacts at the population level, through continual avoidance leading to habitat displacement[317 318] or by reducing energy acquisition in terms of lost feeding opportunities[319]. The displacement of numerous cetacean species has been well documented in the scientific literature[320 321] and, in some cases, individuals have been displaced for a number of years, only returning when the activities causing the anthropogenic noise ceased[322]. If the displacement results in the animals being excluded from important feeding, breeding or nursery habitats then this is likely to have a deleterious impact on survival and growth of the population group[323]. Similarly a prolonged disruption in normal behaviour can reduce foraging time and efficiency. For example, vessel activity is thought to reduce foraging success in killer whales[324] and dolphins[325]. Noise levels generated by vessels in close proximity may be impairing the ability to forage using echolocation by masking echolocation signals[326].

There is growing awareness of the potential problem of chronic stress in marine mammals through the prolonged or repeated activation of the physiological stress response[327], the life-saving combination of systems and events that maximises the ability of an animal to kill or avoid being killed[328]. The goal of this stress response is to enable the animal to survive the perceived immediate threat. Prolonged disturbance of marine mammals to intermittent or continuous anthropogenic noise has the potential to induce a state of chronic stress if the exposures are of sufficient intensity, duration and frequency. The stress response may be triggered repeatedly either through a direct response to sound (e.g., small vessel noise) or indirectly via one or more noise-related impacts (e.g., shipping noise masking communication, navigation or foraging abilities)[329]. Chronic stress is known to have adverse health consequences for populations of terrestrial animals by affecting fertility, mortality and growth rates. Moreover, it is known that a range of biological systems and processes in animals are impacted by exposure to noise: the neuroendocrine system, reproduction and development, metabolism, cardio-vascular health, cognition and sleep, audition

[317] Lusseau, D. 2005. Residency pattern of bottlenose dolphins Tursiops spp. In Milford Sound, New Zealand, is related to boat traffic. Mar. Ecol. Prog. Ser. 295: 265–272

[318] Bejder L, Samuels A, Whitehead H, Gales N and others (2006) Decline in relative abundance of bottlenose dolphins exposed to long-term disturbance. Conserv Biol 20: 1791–1798

[319] Williams R, Lusseau D, Hammond PS (2006) Estimating relative energetic costs of human disturbance to killer whales (*Orcinus orca*). Biol Conserv 133:301–311

[320] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[321] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

[322] Bryant, P.J., Lafferty, C.M., and Lafferty, S.K. (1984). Reoccupation of Laguna Guerrero Negro, Baja California, Mexico by gray whales. In: Jones, M.L., Swartz, S.L., and Leatherwood, S. (ed), the gray whale *Eschrichtius robustus*. Academic Press, Orlando, FL,pp: 375-387

[323] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029

[324] Lusseau, D., Bain, D.E., Williams, R. and Smith, J.C. 2009. Vessel traffic disrupts the foraging behaviour of southern resident killer whales *Orcinus orca*. Endang Species Res 6: 211-221

[325] Allen MC, Read AJ (2000) Habitat selection of foraging bottlenose dolphins in relation to boat density near Clearwater, Florida. Mar. Mamm. Sci .16:815–824

[326] Bain DE, Dahlheim ME (1994) Effects of masking noise on detection thresholds of killer whales. In: Loughlin TR (ed) Marine mammals and the 'Exxon Valdez'. Academic Press, San Diego, CA, p 243–256.

[327] Wright, J.W., Deak, T. and Parsons, E.C.M. 2009. Concerns Related to Chronic Stress in Marine Mammals. IWC SC/61/E16 7 pp.

[328] Romero, L.M. and Butler, L.K. 2007. Endocrinology of stress. *Int. J. Comp. Psych.* 20(2-3):89-95.

[329] Wright, J.W., Deak, T. and Parsons, E.C.M. 2009. Concerns Related to Chronic Stress in Marine Mammals. IWC SC/61/E16 7 pp.

and cochlear morphology, the immune system, and DNA integrity and genes[330]. It therefore seems logical to infer that noise-induced chronic stress has the potential to detrimentally alter similar critical life history parameters in marine mammals (e.g., disease susceptibility, reproductive rates, mortality rates), that may have long-term consequences for populations and should be taken into consideration in terms of conservation planning and management. North Atlantic right whales, for instance, showed lower levels of stress-related fecal glucocorticoids after 9-11 due to decreased shipping with an attendant 6 dB decrease in shipping noise[331].

However, no study to date has found a population level change in marine mammals caused by exposure to anthropogenic noise, though noise is listed as a contributing factor to several species' decline or lack of recovery (e.g., Western gray whales[332] [333] [334] and Southern Resident killer whales[335]. A recent detailed review found little response by cetacean populations to human acoustic disturbance in four case study areas[336], which was attributed to a number of reasons, including the lack of accurate population estimates for marine mammal species and the ability of individuals to adapt and compensate for negative effects[337]. The process by which a temporary change in an individual's behaviour could lead to long-term population level consequences is addressed by the Population Consequence of Acoustic Disturbance (PCAD) Model (Figure 6)[338]. The model, developed for marine mammals but theoretically applicable to other fauna, involves different steps from sound source characteristics through behavioural change, life functions impacted, and effects on vital rates to population consequences.

At the present time most of the variables of the PCAD model are unknown and there are challenges to fill in the current gaps such as uncertainties in population estimates for species or regions, difficulties in weighting noise against other stressors and the inherent inaccessibility of the marine environment[339]. No one factor is likely to be harmful enough to cause a direct population decline in marine life, but a combination of factors may create the required conditions for reduced productivity and survival in some cases[340].

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[330] Kight, C.R. and Swaddle, J.P. 2011. How and why environmental noise impacts animals: an integrative, mechanistic review. Ecology Letters doi: 10.1111/j.1461-0248.2011.01664.x

[331] Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P.,Wasser, S.K., and Kraus, S.D. 2012. Evidence that ship noise increases stress in right whales. Proc. R. Soc. B, doi:10.1098/rspb.2011.2429.

[332] International Whaling Commission. 2007. Report of the scientific committee. Annex K. Report of the Standing Working Group on environmental concerns. J. Cetacean Res. Manag. **9** (Suppl.): 227–296

[333] Weller, D.W., Rickards, S.H., Bradford, A.L., Burdin, A.M., and Brownell, R.L., Jr. 2006*a* . The influence of 1997 seismic surveys on the behavior of western gray whales off Sakhalin Island, Russia. Paper No. SC/58/E4 presented to the International Whaling Commission Scientific Committee, Cambridge, UK.

[334] Weller, D.W., Tsidulko, G.A., Ivashchenko, Y.V., Burdin, A.M., and Brownell, R.L., Jr. 2006*b* . A re-evaluation of the influence of 2001 seismic surveys on western gray whales off Sakhalin Island, Russia. Paper No. SC/58/E5 presented to the International Whaling Commission Scientific Committee, Cambridge, U.K

[335] National Marine Fisheries Service. 2002. Status review under the Endangered Species Act: southern resident killer whales (*Orcinus orca*). NOAA Tech. Mem. NMFS NWFSC-54. Available from http://nwfsc.noaa.gov

[336] Thomsen, F., McCully, S.R., Weiss, L., Wood, D., Warr, K., Kirby, M., Kell, L. and Law, R. 2011. Cetacean stock assessment in relation to exploration and production industry sound: current knowledge and data needs. Aquatic Mammals 37: 1-93. DOI: 10.1578/AM.37.1.2011.1

[337] Tasker, M.L, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

[338] NRC (2005) Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects. National Research Council of the National Academies of Science, Washington, DC.

[339] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[340] Tasker, M.L, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

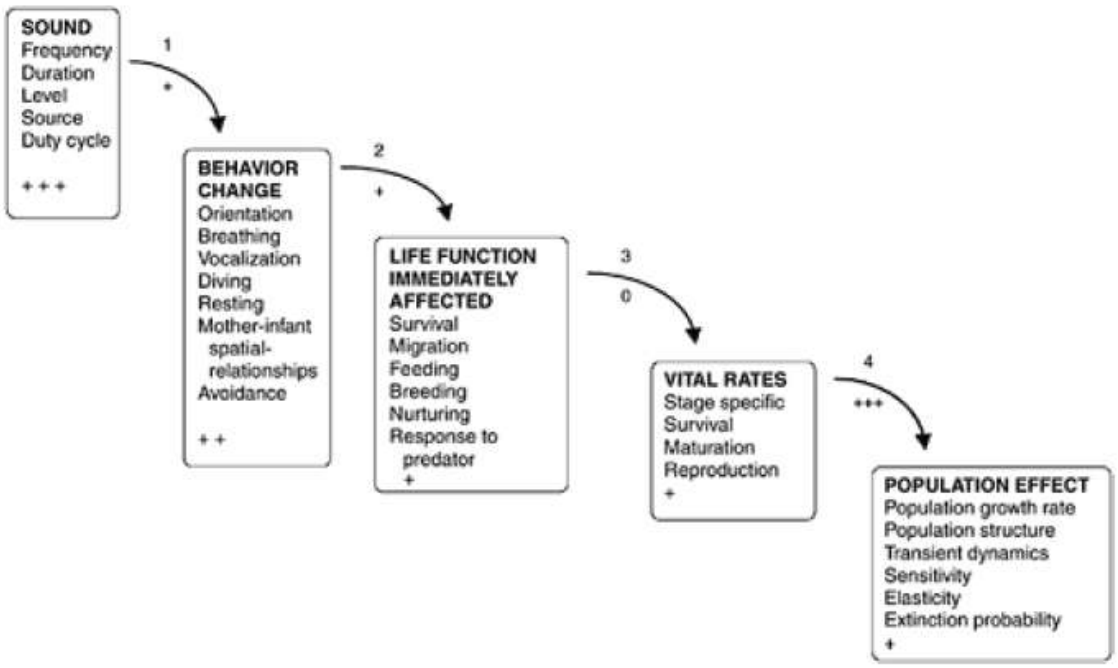

Figure 6. Overview of the PCAD Model by NRC (2005)

Note: The + signs within the boxes indicate how well these features can be measured, while the + signs under the transfer arrows indicate how well these transfer functions are known. As can be seen, some transfer functions such as 1-3 are not well known.

The potential impacts of sound also need to be considered in a wider context, through addressing the consequences of acoustic disturbance on populations in conjunction with other stressors such as bycatch mortality, overfishing leading to reduced prey availability and other forms of pollution such as persistent organic pollutants[341] [342]. These various stressors may also act synergistically or cumulatively. For example underwater noise could interact with bycatch or collision issues in that the individual is less able to detect the presence of fishing nets or nearby vessels[343]. Multiple sources of anthropogenic sound may also interact cumulatively or synergistically such as when naval sonar emissions from multiple vessels produce confusing sound fields[344].

IMPACTS ON MARINE FISH

In comparison to marine mammals research into the effects of anthropogenic noise on marine fish is still very much in its infancy and there is far less information available[345] [346]. Much of the material available is

[341] Perrin, W.F, Würsig, B. and Thewissen, J.G.M. (eds) (2002). Encyclopedia of Marine Mammals. Academic Press, San Diego.

[342] Read, A.J., Drinker, P. and Northridge, S.P. (2006). By-catches of marine mammals in U.S. and global fisheries. Conservation Biology, 20: 163-169.

[343] Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

[344] Ibid

[345] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[346] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

also technical reports or 'grey literature' and has not always been through the scientific peer review process[347]. A recent evaluation of both the peer-reviewed and grey literature concluded that on the whole very little is known about the effects of anthropogenic sound on fish and stressed the need for a systematic programme of study on a range of species[348].

Marine fish are susceptible to the same range of effects as has been discussed previously for marine mammals although the principles of hearing differ somewhat between the two groups and these differences influence how noise impact assessments should be conducted[349]. The impacts of intense sound over short periods have been studied in some detail with respect to physical trauma and behaviour[350] [351] [352] [353] but there are currently hardly any data available for the effects of ambient noise on fish behaviour[354]. Where data are lacking, inferences can be drawn from assessing noise-related impacts on the behaviour of other vertebrates[355]. For fish it is also important to consider the effects of noise on eggs and larvae.

A. INJURY AND PHYSICAL EFFECTS

Hearing loss and auditory damage

Temporary deafness could result in a fish being unable to respond to other environmental sounds that indicate the presence of predators and facilitate the location of prey and mates[356]. Most of the studies investigating hearing loss in fish have been laboratory-based using different types of sound (e.g., pure tones or white noise) and exposure durations with mixed results. There are only a few field-based studies of auditory effects involving actual anthropogenic sound sources (seismic surveys and military sonar) experienced at sea or using playbacks of sounds. Laboratory work on two freshwater species showed that temporary loss of hearing (i.e., temporary threshold shifts [TTS]), can occur at sound pressure levels (SPL) of 140–170 dB re 1 µPa and hearing loss did not recover for at least two weeks after exposure[357]. A significant hearing threshold shift was reported for rainbow trout exposed to a playback of low-frequency active sonar at an SPL of 193 dB re 1 µPa[358]. However, a field-based study of hearing loss in four coral

[347] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[348] Ibid

[349] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[350] Hastings, M.C. and Popper, A.N. 2005. Effects of sound on fish. Contract 43A0139 Task Order 1, California Department of Transportation. 82pp.

[351] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[352] Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D.T. & Thomsen, F. (2010) Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report

[353] McCauley, R. D., Fewtrell, J. & Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears. Journal of the Acoustical Society of America 113, 638–642

[354] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

[355] Ibid

[356] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[357] Ibid

[358] Popper, A. N., Halvorsen, M. B., Kane, E., Miller, D. D., Smith, M. E., Song, J., Stein, P. & Wysocki, L. E. (2007). The effects of high-intensity, low-frequency active sonar on rainbow trout. Journal of the Acoustical Society of America 122, 623–635

reef fish species during a seismic survey did not find any loss of hearing up to 193 dB re 1 µPa[359]. Hearing impairment (TTS) associated with long-term, continuous exposure (2 hours), and masked hearing thresholds have been reported for fish exposed to simulated noise (playback) of small boats and ferries[360] [361]. Overall the amount of hearing loss in fish appears to be related to the noise intensity compared to the threshold of hearing at that frequency. At frequencies where a fish was more sensitive (i.e., had a lower threshold), TTS produced by constant, broadband white noise was greater[362]. Considerable further research of this subject is required, particularly in a field-based setting using a variety of actual anthropogenic noise sources.

Damage to sensory hair cells of the inner ear of fish exposed to sound has been reported in a few studies[363] [364] [365] but not in others[366] [367]. In a field-based study using caged fish exposed to a seismic air gun some of these hair cells were severely damaged and showed no signs of recovery after 58 days[368]. Furthermore, the hair cell damage recorded in these studies was only a visual manifestation of what may have been a much greater effect[369]. Damage to the lateral line organ in fish has also been proposed when individuals are in close proximity to an intense sound source[370] and the suggested mechanism for this is the decoupling of the cupulae from the neuromasts[371].

Non-auditory damage

The swim bladder of a fish is a gas-filled structure that is susceptible to damage by sound. In addition, sound will cause gas organs such as the swim bladder and lung to oscillate and push on the surrounding tissues. Gas oscillations induced by high SPLs can potentially cause the swim bladder to tear or rupture[372]. Ruptured swim bladders have been reported in fish exposed to explosions[373] [374] [375], and to pile

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359 Hastings, M. C., Reid, C. A., Grebe, C. C., Hearn, R. L. & Colman, J. G. (2008). The effects of seismic airgun noise on the hearing sensitivity of tropical reef fishes at Scott Reef, Western Australia. Underwater Noise Measurement, Impact and Mitigation, Proceedings of the Institute of Acoustics 30 (5).

360 Scholik, A.R. and H. Y. Yan. 2001. Effects of underwater noise on auditory sensitivity of a cyprinid fish. Hearing Research 152, 17-24.

361 Vasconcelos, R. O., M. C. P. Amorim, and F. Ladich. 2007. Effects of ship noise on the detectability of communication signals in the Lusitanian toadfish. Journal of Experimental Biology 210, 2104-2112.

362 OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

363 Enger, P. S. (1981). Frequency discrimination in teleosts – central or peripheral? In *Hearing and Sound Communication in Fishes* (Tavolga, W. N., Popper, A. N. & Fay, R. R., eds), pp. 243–255. New York, NY: Springer-Verlag.

364 Hastings, M. C., Popper, A. N., Finneran, J. J. & Lanford, P. J. (1996). Effect of low frequency underwater sound on hair cells of the inner ear and lateral line of the teleost fish Astronotus ocellatus. Journal of the Acoustical Society of America 99, 1759–1766.

365 McCauley, R. D., Fewtrell, J. & Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears. Journal of the Acoustical Society of America 113, 638–642

366 Popper, A. N., Halvorsen, M. B., Kane, E., Miller, D. D., Smith, M. E., Song, J., Stein, P. & Wysocki, L. E. (2007). The effects of high-intensity, low-frequency active sonar on rainbow trout. Journal of the Acoustical Society of America 122, 623–635

367 Song, J., Mann, D. A., Cott, P. A. Hanna, B. W. & Popper, A. N. (2008). The inner ears of northern Canadian freshwater fishes following exposure to seismic air gun sounds. Journal of the Acoustical Society of America 124, 1360–1366.

368 McCauley, R. D., Fewtrell, J. & Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears. Journal of the Acoustical Society of America 113, 638–642

369 Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

370 Ibid

371 Denton, E. J. & Gray, J. A. B. (1993). Stimulation of the acoustico-lateralis system of clupeid fish by external sources and their own movements. Philosophical Transactions of the Royal Society B: Biological Sciences 341, 113–127.

372 Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

driving sound in some studies[376 377] but not others[378]. Low-frequency sonar has the potential to damage swim bladders or adjacent tissue if the frequency emitted matches the resonance frequency of a particular fish species. Most fish are likely to show resonance frequencies between 100 and 500 Hz[379]. Fish that do not possess swim bladders such as flatfish are less susceptible to damage from explosions[380]. 'Blast fishing' explosions on tropical coral reefs not only kill and injure fish and invertebrates but cause extensive damage to reef habitat[381]. Blasts occurring during the decommissioning of oil and gas platforms can also cause in fish mortality[382]. It has been suggested that fish may be susceptible to two types of tissue damage when exposed to intense sound[383]. Firstly sufficiently high sound levels are known to cause the formation of micro-bubbles in the blood and fat tissue[384]. Bubble growth by rectified diffusion[385] at low frequencies could create an embolism and either burst small capillaries to cause superficial or internal bleeding, or cause damage to fish eyes where tissue may have high gas saturation[386]. Secondly, exposure to transient high level sound may cause traumatic brain injury. Fish with swim-bladder projections or other air bubbles near the ear (to enhance hearing) could potentially be susceptible to neurotrauma when exposed to high SPLs[387].

Studies of the effect of impulsive sound (seismic air guns) on the eggs and larvae of marine fish observed decreased egg viability, increased embryonic mortality, or decreased larval growth when exposed to sound levels of 120 dB re 1 μPa[388 389]. Turbot larvae also suffered damage to brain cells and to neuromasts

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[373] Aplin, J. A. (1947). The effect of explosives on marine life. California Fish and Game 33, 23–30.

[374] Coker, C. M. and Hollis, E. H. (1950). Fish mortality caused by a series of heavy explosions in Chesapeake Bay. Journal of Wildlife Management 14, 435–445.

[375] Wiley, M. L., Gaspin, J. B. & Goertner, J. F. (1981). Effects of underwater explosions on fish with a dynamical model to predict fishkill. Ocean Science and Engineering 6, 223–284.

[376] Caltrans. (2001). Pile installation demonstration project, fisheries impact assessment. PIDP EA 012081. San Francisco–Oakland Bay Bridge East Span Seismic Safety Project. Caltrans Contract 04A0148 San Francisco, CA: Caltran.

[377] Caltrans. (2004). Fisheries and hydroacoustic monitoring program compliance report for the San Francisco–Oakland bay bridge east span seismic safety project. Caltrans Contract EA12033. San Francisco, CA: Caltrans.

[378] Nedwell, J, Turnpenny, A., Langworthy, J. & Edwards, B. (2003). Measurements of underwater noise during piling at the Red Funnel Terminal, Southampton, and observations of its effect on caged fish. Subacoustics LTD. Report 558 R 0207. Bishops Waltham: Subacoustic Ltd.

[379] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[380] Goertner, J. F., Wiley, M. L., Young, G. A. & McDonald, W. W. (1994). Effects of underwater explosions on fish without swimbladders. Naval Surface Warfare Center Report NSWC TR88-114. Fort Belvoir, VA: Defence Technical Information Center.

[381] Saila, S.B., Kocic, V. Lj., and McManus, J.W. (1993). Modelling the effects of destructive practices on tropical coral reefs. Mar. Ecol. Progr. Ser. 94: 51-60.

[382] Gitschlag, G.R. and Herczeg, B.A. (1994). Sea turtle observations at explosive removals of energy structures. Mar. Fish. Rev., 56: 1-8.

[383] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[384] ter Haar, G., Daniels, S., Eastaugh, K. C. & Hill, C. R. (1982). Ultrasonically induced cavitation in vivo. British Journal of Cancer 45 (Suppl.V), 151–155.

[385] Crum, L. A. & Mao, Y. (1996). Acoustically enhanced bubble growth at low frequencies and its implications for human diver and marine mammal safety. Journal of the Acoustical Society of America 99, 2898–2907.

[386] Turnpenny, A. W. H., Thatcher, K. P. & Nedwell, J. R. (1994). The effects on fish and other marine animals of high-level underwater sound: Contract Report FRR 127/94. Southampton: Fawley Aquatic Research Laboratories, Ltd.

[387] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[388] Kostyuchenko, L.P. 1973. Effects of elastic waves generated in marine seismic prospecting of fish eggs in the Black Sea. Hydrobiol. Jour. 9 (5): 45-48.

[389] Booman, C., Dalen, J., Leivestad, H, Levsen, A., van der Meeren, T. and Toklum, K. 1996. Effects from airgun shooting on eggs, larvae, and fry. Experiments at the Institute of Marine Research and Zoological Laboratorium, University of Bergen. (In Norwegian. English summary and figure legends). Institute of Marine Research. Fisken og havet No. 3 - 1996. 83 pp

of the lateral line[390]. The neuromasts are thought to play an important role in escape reactions for many fish larvae, and thus their ability to avoid predators[391]. Injuries and increased mortality from air guns occurred at distances less than 5 m from the sound source. The most frequent and serious injuries occur within 1.5 m and fish in the early stages of life were most vulnerable[392]. Juveniles and fry have less inertial resistance to the motion of a passing sound wave, and so are potentially more at risk for non-auditory tissue damage than adult fish[393].

The very limited data available for the effects of sonar on fish show no evidence of tissue damage or mortality to adult fish[394]. Studies focussed on larval and juvenile fish exposed to mid-frequency sonar recorded significant mortality (20-30%) of juvenile herring in 2 of 42 experiments[395], which was estimated in a 'worst-case' scenario to be equivalent to a lower mortality rate than would occur due to natural causes in the wild[396]. However, there is a need to repeat these experiments as the sound level was only tested once and so it is unknown if the increased mortality was due to the level of the test signal or to other unknown factors[397].

B. BEHAVIOURAL DISTURBANCE

There have been very few studies to determine the effects of anthropogenic noise on marine fish behaviour to date and nothing at all is known about the long-term effects of exposure to sound or about the effects of cumulative exposure to loud sounds[398]. Fish behaviour is also often observed in a cage or tank, which can provide some useful information regarding the initial response to a sound[399] but is not representative of behaviour when exposed to the same sound in the wild, for example in a spawning or feeding ground[400]. The response to sounds by fish can range from no change in behaviour to mild "awareness" of the sound or a startle response (but otherwise no change in behaviour), to small temporary movements for the duration of the sound, to larger movements that might displace fish from their normal locations for short or long periods of time[401]. Depending on the level of behavioural change, there may be no real impact on individuals or populations or substantial changes (e.g., displacement from a feeding or breeding site or disruption of critical functions) that affect the survival of individuals or populations[402] [403].

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[390] Ibid

[391] Blaxter, J.H.S. and Hoss, D.E. 1981. Startle response in herring: The effect of sound stimulus frequency, size of fish and selective interference with the acoustico-lateralis system. J. Mar. Biol. Assoc. UK 61: 871-879

[392] Booman, C., Dalen, J., Leivestad, H, Levsen, A., van der Meeren, T. and Toklum, K. 1996. Effects from airgun shooting on eggs, larvae, and fry. Experiments at the Institute of Marine Research and Zoological Laboratorium, University of Bergen. (In Norwegian. English summary and figure legends). Institute of Marine Research. Fisken og havet No. 3 - 1996. 83 pp

[393] Popper, A.N., and Hastings, M.C. 2009b. The effects of human-generated sound on fish. Integrative Zoology, 4: 43 – 52.

[394] Ibid

[395] Jørgensen, R., Olsen, K. K., Falk-Petersen, I. B. & Kanapthippilai, P. (2005). Investigations of Potential Effects of Low Frequency Sonar Signals on Survival, Development and Behaviour of Fish Larvae and Juveniles. Norway: Norwegian College of Fishery Science, University of Tromsø.

[396] Kvadsheim, P. H. & Sevaldsen, E. M. (2005). The Potential Impact of 1–8 kHz Active Sonar on Stocks of Juvenile Fish During Sonar Exercises. FFI/Report- 2005/01027.Kjeller: Norwegian Defence Research Establishment.

[397] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[398] Ibid

[399] Sara, G. et al. (2007) Effect of boat noise on the behaviour of Bluefin tuna Thunnus thynnus in the Mediterranean Sea. Mar. Ecol.-Prog. Ser. 331, 243–253.

[400] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[401] Ibid

[402] Ibid

[403] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

Moreover, there could be long-term effects on reproduction and survival in species that are subject to national or international conservation efforts and/or commercial interest[404].

An alarm or escape reaction, can be triggered when fish receive a strong sound stimulus[405 406]; such as an air-gun array[407]and the reaction is often characterised by a typical "C-start" response, where the body of the fish forms a 'C' and points away from the sound source[408].

Avoidance behaviour of vessels, vertically or horizontally in the water column, has been reported for cod and herring, and was attributed to vessel noise[409 410]. Vessel activity can also alter schooling behaviour and swimming speed of fish[411]. Relatively low levels of pile driving noise played to cod and sole caused changes in swimming speed, a freezing response and directional movement away from the sound[412]. Large-scale avoidance behaviour was inferred from studies of the effect of seismic surveys on catch rates in long-line and trawl fisheries. Significant declines in catches of cod and haddock were recorded up to 25 miles from the air-gun source, which was the maximum distance examined, and catch rates did not recover until five days after the seismic survey ceased, which was the maximum time observed[413 414]. Similarly, a 52% decrease in rockfish catch was reported when the catch area was exposed to a single air-gun array[415] which may have been caused by a change in swimming depth or shoaling behaviour[416]. Pelagic species such as blue whiting reacted to air guns by diving to greater depths but also by an increased abundance of fish 30–50 km away from the affected area, suggesting that migrating fish would not enter the zone of seismic activity[417]. Conversely, a study using direct video observation showed that temperate reef fish remained close to their territories after exposure to air-gun arrays with only minor behavioural responses observed[418]. Mid-frequency active sonar did not elicit a significant behavioural

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[404] Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D.T. & Thomsen, F. (2010) Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report.

[405] Blaxter, J.H.S. & hoss, d.e. 1981: Startle Response in herring: The effect of sound stimulus frequency,size of fish and selective interference with the acoustic-Lateralis system. J. Mar. Biol. Ass., U.K. 61: 871-879.

[406] Popper, A. N. & Carlson, T. J. 1998: Application of sound and other stimuli to control fish behaviour. Transactions of the American Fisheries Society 127(5): 673-707.

[407] Hassel, A., Knutsen, T., Dalen, J., Skaar, K. Løkkeborg, S., Misund, O. A., Østensen, Ø., Fonn, M. & Haugland, E. K. (2004). Influence of seismic shooting on the lesser sandeel (*Ammodytes marinus*). ICES Journal of Marine Science 61, 1165–1173.

[408] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[409] Vabø, R. et al. (2002) The effect of vessel avoidance of wintering Norwegian spring-spawning herring. Fish. Res. 58, 59–77

[410] Handegard, N.O. et al. (2003) Avoidance behavior in cod, *Gadus morhua*, to a bottom trawling vessel. Aqua. Liv. Res. 16, 265–270

[411] Sara, G. et al. (2007) Effect of boat noise on the behaviour of Bluefin tuna *Thunnus thynnus* in the Mediterranean Sea. Mar. Ecol.-Prog. Ser. 331, 243–253.

[412] Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D.T. & Thomsen, F. (2010) Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report.

[413] Engås, A., Løkkeborg, S., Ona, E. & Soldal, A. V. (1996). Effects of seismic shooting on local abundance and catch rates of cod (Gadus morhua) and haddock (Melanogrammus aeglefinus). Canadian Journal of Fisheries and Aquatic Science 53, 2238–2249.

[414] Engås, A. & Løkkeborg, S. (2002). Effects of seismic shooting and vessel-generated noise on fish behaviour and catch rates. Bioacoustics 12, 313–315.

[415] Skalski, J. R., Pearson, W. H. & Malme, C. I. (1992). Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hook-and-line fishery for rockfish (Sebastes spp.). Canadian Journal of Fisheries and Aquatic Sciences 49, 1357–1365.

[416] Wardle, C. S., Carter, T. J., Urquhart, G. G., Johnstone, A. D. F., Ziolkowski, A. M., Hampson, G. & Mackie, D. (2001). Effects of seismic air guns on marine fish. Continental Shelf Research 21, 1005–1027.

[417] Slotte, A., Kansen, K., Dalen, J. & Ona, E. (2004). Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. Fisheries Research 67, 143–150.

[418] Wardle, C. S., Carter, T. J., Urquhart, G. G., Johnstone, A. D. F., Ziolkowski, A. M., Hampson, G. & Mackie, D. (2001). Effects of seismic air guns on marine fish. Continental Shelf Research 21, 1005–1027.

response in herring in terms of vertical or horizontal escape reactions[419]. ADD's (or pingers) which produce frequencies lower than 10 kHz and have a source level above 130 dB re 1 μPa are likely to have a significant influence on the behaviour of fish[420]. Although the responses of fish to commercially available acoustic harassment devices (AHDs) have not been thoroughly tested it is thought that AHDs which produce substantial energy in the ultrasonic range may cause some behavioural avoidance responses in fish with good ultrasonic hearing but only close to the device (within 20 metres)[421].

A recent study of foraging performance in three-spined sticklebacks exposed to acoustic noise found that the addition of noise resulted in decreased foraging efficiency, with more attacks needed to consume the same number of prey items[422]. Acoustic noise increased food-handling errors and reduced discrimination between food and non-food items, results that are consistent with a shift in attention. In this case noise may have attracted the attention of the fish, thus preventing them from focusing fully on foraging.

Increased levels of anthropogenic noise in the marine environment may also invoke a stress response in fish. Studies of captive freshwater fish exposed to simulated boat noise for 30 minutes found increased level of the stress hormone cortisol in the blood[423]. Noise-related increases in heart rate and muscle metabolism have also been reported for captive fish[424] [425]. Although data are lacking for wild fish in terms of noise-related stress effects, these studies at least suggest that anthropogenic noise could be a stressor in natural water bodies[426]. Stress is known to affect health and well-being in terrestrial vertebrates by influencing processes such as growth and reproduction. Highly stressed fish may also be more susceptible to predation or other environmental effects than non-stressed fish[427]. The issue of noise-related stress in marine fish is clearly in need of investigation in the natural environment which may involve developing new analytical techniques to accurately measure stress levels '*in situ'*.

C. MASKING

Masking by anthropogenic noise can affect fish in two main ways, by interfering with acoustic communication or through the masking of important environmental auditory cues.

The potential for masking of acoustic communication in marine fish is considerable. Over 800 species from 109 families of bony fish are known to produce sounds and many more species are suspected to do

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[419] Doksæter, L., Godø, O. R., Handegard, N. O., Kvadsheim, P.H., Lam, F.-P. A., Donovan, C. and Miller, P. J. O. 2009. Behavioral responses of herring (*Clupea harengus*) to 1–2 and 6–7 kHz sonar signals and killer whale feeding sounds. Journal of the Acoustical Society of America 125: 554-564.

[420] Kastelein, R. A., S. van der Heul, J. van der Veen, W. C. Verboom, N. Jennings, D. de Haan, and P. J. H. Reijnders. 2007. Effects of acoustic alarms, designed to reduce small cetacean bycatch in gillnet fisheries, on the behaviour of North Sea fish species in a large tank. Marine Environmental Research 64:160-180.

[421] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[422] Purser J, Radford AN (2011) Acoustic Noise Induces Attention Shifts and Reduces Foraging Performance in Three-Spined Sticklebacks (Gasterosteus aculeatus). PLoS ONE 6(2): e17478. doi:10.1371/journal.pone.0017478

[423] Wysocki, L.E. et al. (2006) Ship noise and cortisol secretion in European freshwater fishes. Biol. Conserv. 128, 501–508

[424] Graham, A.L. and Cooke, S.J. (2008) The effects of noise disturbance from various recreational boating activities common to inland waters on the cardiac physiology of a freshwater fish, the largemouth bass (Micropterus salmoides). Aquatic Conserv: Mar. Freshw. Ecosyst. 18, 1315–1324

[425] Buscaino, G. et al. 2009. Impact of an acoustic stimulus on the motility and blood parameters of European sea bass (Dicentrarchus labrax L.) and gilthead sea bream (Sparus aurata L.). Mar. Environ. Res. 69, 136–142

[426] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

[427] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

so[428 429]. The majority of fish species detect sounds from below 50 Hz up to 500–1500 Hz with most communication signals in fish falling within a frequency band between 100 Hz and 1 kHz[430431], which overlaps with low frequency shipping noise. There are also a small number of species that can detect sounds to over 3 kHz, while a very few species can detect sounds to well over 100 kHz[432]. Fish are known to produce sounds during territorial fighting, when competing for food or when being attacked by a predator[433]. Acoustic communication can also be extremely important for courtship interactions[434] and in spawning aggregations[435]. Masking of the sounds produced by fish for mate detection and recognition, or for aggregating reproductive groups may therefore have significant fitness consequences for populations. Noise produced by boat traffic has been shown to reduce the effective range of communication signals and therefore the signalling efficiency between individual fish in freshwater environments[436 437]. A study in the Mediterranean Sea revealed that recreational boat noise can significantly increase detection threshold levels for conspecific sounds in brown meagre drums and damselfish, and it was inferred that passing vessels were reducing detection distances in this environment by up to 100 times[438]. Signals may also be detected but not fully understood as some of the required information in the signal is lost. Although not reported in marine fish to date, a reduction in detection distance that influenced mate attraction was reported in birds[439], while sexual signals for mate selection in frogs[440] have been masked in noisy conditions. Some fish communities that are located in busy shipping lanes or noisy coastal areas are likely to be restricted in their ability to detect and respond to acoustic signals.

Anthropogenic noise may also interfere with prey or predator detection in marine fish[441]. Predator avoidance by fish may depend on species hearing or localizing specific sounds. For example some herring species (Clupeidae) of the genus *Alosa* are capable of detecting ultrasound (up to 180 kHz), which could allow them to detect and avoid echo-locating whales[442]. Studies on European eels and juvenile salmonids revealed that they are able to detect and avoid infrasound (<20 Hz), which may allow them to sense the

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[428] Ladich, F. (2004) Sound production and acoustic communication. In The Senses of Fish: Adaptations for the Reception of Natural Stimuli (von der Emde et al., eds),pp. 210–230, Kluwer Academic Publishers & Narosa Publishing House

[429] Kasumyan, A.O. (2008) Sound and sound production in fishes. J. Ichthyol. 11, 981–1030

[430] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[431] Zelick, R., D. A. Mann, and A. N. Popper. 1999. Acoustic communication in fishes and frogs, p. 363-411. *In* A. P. Popper and R. R. Fay (ed.), Comparative Hearing: Fish and Amphibians, Springer Verlag, New York

[432] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489

[433] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

[434] Myrberg, A.A. et al. (1986) Sound production by males of a coral reef fish (Pomacentrus partitus): its significance to females. Anim. Behav. 34, 913–923

[435] Aalbers, S.A. (2008) Seasonal, diel, and lunar spawning periodicities and associated sound production of white seabass (Atractoscion nobilis). Fishery Bull. 106, 143–151

[436] Amoser, S., Wysocki, L.E., Ladich, F., 2004. Noise emission during the first powerboat race in an Alpine lake and potential impact on fish communities. J. Acoust. Soc. Am. 116, 3789–3797.

[437] Vasconcelos, R.O., Amorim, M.C.P., Ladich, F., 2007. Effects of ship noise on the detectability of communication signals in the Lusitanian toadfish. J. Exp. Biol. 210, 2104–2112.

[438] Codarin, A., et al. Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). Mar. Pollut. Bull. (2009), doi:10.1016/j.marpolbul.2009.07.011

[439] Habib, L. et al. (2006) Chronic industrial noise affects pairing success and age structure of ovenbirds Seiurus aurocapilla. J. Appl. Ecol. 44, 176–184

[440] Wollerman, L. and Wiley, R.H. (2002) Background noise from a natural chorus alters female discrimination of male calls in a neotropical frog. Anim. Behav. 63, 15–22

[441] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243

[442] Dokseater, L. et al. (2009) Behavioral responses of herring (Clupea harengus) to 1-2 and 6-7 kHz sonar signals and killer whale feeding sounds. J. Acoust. Soc. Am. 125, 554–564

hydrodynamic noise generated by approaching predators[443 444]. It has been suggested that predators that use sound for hunting can be restricted by noisy conditions through lower availability of suitable foraging areas (habitat displacement) and a lower catching efficiency[445]. The latter has also recently been shown for predatory fish that rely on vision to catch prey and was attributed to the sound interfering with the attention span of the fish, distracting it from feeding[446].

Anthropogenic masking of natural acoustic cues that are important for the orientation of marine fish may also be occurring in coastal environments. The noise generated by temperate or tropical (coral) reef communities is one of the cues used by the pelagic larval stages of reef fish for orientation prior to settlement[447 448 449]. Fish larvae have also been shown to return to their natal reef[450 451], most probably using acoustic and chemical cues for locating the settlement habitat. Recent studies of reef noise indicate that habitats within coral reefs produce different acoustic profiles[452] that are used by some species of juvenile reef fish for nocturnal orientation[453]. It has also been found that reef fish larvae, after several hours of exposure, can become attracted to artificial sounds that would normally be avoided[454]. It has also been suggested that increased levels of noise may inhibit orientation / settlement of fish larvae on coral reefs by masking the necessary acoustic cues received by larval fish[455]. It does appear that anthropogenic noise has the potential to negatively influence the recruitment of fish larvae onto temperate or tropical reef systems but this needs verification. Shipping noise from engines has also been shown to attract settlement of mussel larvae, causing biofouling of ship hulls[456].

Anthropogenic-induced degradation of marine habitats such as coral reefs may also indirectly influence larval orientation and recruitment to habitats by changing the acoustic profile of these habitats. Quieter habitats combined with increasing anthropogenic noise may have an impact on larval recruitment through reduced settlement[457].

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[443] Sand, O. et al. (2000) Avoidance responses to infrasound in downstream migrating European silver eels, Anguilla anguilla. Environ. Biol. Fishes 57, 327–336

[444] Knudsen, F.R. et al. (1997) Infrasound produces flight and avoidance response in Pacific juvenile salmonids. J. Fish Biol. 51, 824–829

[445] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243.

[446] Purser J, Radford AN (2011) Acoustic Noise Induces Attention Shifts and Reduces Foraging Performance in Three-Spined Sticklebacks (Gasterosteus aculeatus). PLoS ONE 6(2): e17478. doi:10.1371/journal.pone.0017478

[447] Leis, J.M., Carson-Ewart, B.M., Hay, A.C., Cato, D.H., 2003. Coral-reef sounds enable nocturnal navigation by some reef-fish larvae in some places and at some times. J. Fish. Biol. 63, 724–737.

[448] Simpson SD, Meekan M, Montgomery J, McCauley R, Jeffs A. 2005. Homeward sound. Science 308:221.

[449] Montgomery, J.C., Jeffs, A., Simpson, S.D., Meekan, M., Tindle, C., 2006. Sound as an orientation cue for the pelagic larvae of reef fishes and decapod crustaceans. Adv. Mar. Biol. 51, 143–196.

[450] Jones GP, Planes S, Thorrold SR (2005) Coral reef fish larvae settle close to home. Curr Biol 15:1314–1318

[451] Almany GR, Berumen ML, Thorrold SR, Planes S, Jones GP (2007) Local replenishment of coral reef fish populations in a marine reserve. Science 316:742–744

[452] Kennedy EV, Guzman HM, Holderied MW, Mair JM, Simpson SD (2010) Reef generated noise provides reliable information about habitats and communities: evidence from a Panamanian case study. J Exp Mar Biol Ecol 395: 85–92

[453] Radford CA, Stanley JA, Simpson SD, Jeffs AG (2011) Juvenile coral reef fishes use sound to locate habitats. Coral Reefs, 30:295-305

[454] Simpson SD, Meekan MG, Larsen NJ, McCauley RD, Jeffs A (2010) Behavioural plasticity in larval reef fish: orientation is influenced by recent acoustic experiences. Behav Ecol 21: 1098–1105.

[455] Simpson SD, Meekan MG, Jeffs A, Montgomery JC, McCauley RD. 2008. Settlement-stage coral reef fishes prefer the higher frequency invertebrate-generated audible component of reef noise. Anim Behav 75:1861–8.

[456] Wilkens, S.L., Stanley, J.A., Jeffs A.G. 2012. Induction of settlement in mussel (*Perna canaliculus*) larvae by vessel noise, Biofouling: The Journal of Bioadhesion and Biofilm Research, 28:1, 65-72.

[457] Leis, J.M., Siebeck, U. and Dixon, D. How nemo finds homes:The neuroecology of dispersal and of population connectivity in larvae of marine fishes. Integrative and Comparative Biology, volume 51, number 5, pp. 826–843

This section has reviewed in some detail the known and potential impacts of anthropogenic noise on marine teleost fish but elasmobranchs (sharks, skates and rays) have not been mentioned until now. In fact there are no reported studies of the effects of anthropogenic noise exposure on elasmobranchs and only a few experiments exploring behavioural responses to sound in sharks (but not skates or rays)[458]. Studies of acoustic attraction in 18 species of coastal and oceanic sharks found that individuals would approach underwater speakers broadcasting low-frequency, erratically pulsed sounds from a distance of several hundred metres[459]. A few studies investigating avoidance behaviour, found that sudden loud sounds (20-30 dB above ambient noise levels) played when a shark approached a location would startle the shark and cause it to turn away from the area. In most cases involving attraction and repulsion, the sharks would habituate to the stimuli after a few trials[460].

Elasmobranchs do not have a swim bladder or any other air-filled cavity, meaning that they are incapable of detecting sound pressure. Therefore particle motion is assumed to be the only sound stimulus that can be detected. The hearing bandwidth for elasmobranchs has been measured as between 20 Hz and 1 kHz, with similar thresholds in all species above 100 Hz[461]. Elasmobranchs do not appear to be as sensitive to sound as teleost fish when measured in comparable ways[462]. However, the current knowledge of elasmobranch hearing is based on data from only a few of the hundreds of species, and so one must be cautious in making generalizations about an entire subclass of fishes based on these data[463].

Anthropogenic noise sources that have the potential to affect elasmobranchs are thought to be pile driving, wind turbines and boat noise[464]. Elasmobranchs have been reported to aggregate around coastal and offshore man-made structures[465]. High intensity sounds produced by pile driving could damage hearing in elasmobranchs in the form of a TTS and result in a temporary loss of sensitivity[466]. Secondly the impact of the hammer on the pile may cause barotrauma in elasmobranchs and this has recently been reported in some organs in teleost fish including the liver and kidneys[467]. Demersal elasmobranchs such as skates and rays may also be damaged by the intense vibrations in the sediments that are caused by pile driving[468]. The continuous low frequency sound produced by operating turbines in offshore wind farms could potentially mask sounds that are important to elasmobranchs. Similarly, shipping noise may mask biologically important sounds or result in some of the effects observed in teleost fish also occurring in elasmobranchs (e.g., the production of stress hormones)[469]. It is clear that extensive research is required to assess the effects of anthropogenic noise on elasmobranch (and also teleost) fish in the marine and coastal environment.

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458 Casper, B.M., Halvorson, M.B. and Popper, A.N. (in press). Are sharks even bothered by a noisy environment?

459 Myrberg AA Jr (2001) The acoustical biology of elasmobranchs. Environ Biol Fish 60:31-45.

460 Casper, B.M., Halvorsen, M.B. and Popper, A.N. (in press). Are sharks even bothered by a noisy environment?

461 Casper and Mann 2009

462 Casper, B.M., Halvorsen, M.B. and Popper, A.N. (in press). Are sharks even bothered by a noisy environment?

463 Ibid

464 Ibid

465 Stanley DR, Wilson CA (1991) Factors affecting the abundance of selected fishes near oil and gas platforms in the Northern Gulf of Mexico. Fish Bull 89:149-159.

466 Casper, B.M., Halvorsen, M.B. and Popper, A.N. (in press). Are sharks even bothered by a noisy environment?

467 Halvorsen et al., (in press)

468 Casper, B.M., Halvorsen, M.B. and Popper, A.N. (in press). Are sharks even bothered by a noisy environment?

469 Ibid

IMPACTS ON OTHER MARINE ORGANISMS

Other marine animals that are sensitive to underwater sound include marine turtles[470], and many invertebrates[471] [472]. There is very limited information available for the effects of anthropogenic noise on these marine taxa at the present time although research and conservation interest is growing in these fields.

MARINE TURTLES

Marine turtles are sensitive to low frequency sounds within the range of 100 to 1000 Hz with greatest sensitivity between 200 to 400 Hz[473]. As for invertebrates only studies involving air-gun arrays and their effect on marine turtles have been completed to date. These studies are either experimental where enclosed individuals are exposed to air guns or are part of monitoring assessments conducted during seismic surveys from the survey vessel[474]. Most experimental studies to assess short-term responses have demonstrated a strong initial avoidance response in marine turtles to air-gun arrays[475] [476] [477] at a strength of 175 dB re 1µPa rms or greater. Enclosed turtles also responded less to successive air-gun shots which may have been caused by reduced hearing sensitivity (TTS). For example, one turtle experienced a TTS of 15dB and recovered two weeks later[478]. It was estimated in one study that a typical air-gun array operating in 100–120 m water depth, could cause behavioural changes at a distance of ~2 km and avoidance at around 1 km for marine turtles[479]. A recent monitoring assessment recorded that 51% of turtles dived at or before their closest point of approach to the air-gun array[480].

Long-term exposure to high levels of low frequency anthropogenic noise in coastal areas that are also vital habitat may affect turtle behaviour and ecology[481]. Avoidance behaviour may result in significant changes in turtle distribution with potential consequences for individuals or populations if displaced from their preferred feeding habitat[482]. At lower sound levels turtles that remain in an affected area may show abnormal behaviour that reduces their foraging efficiency. However there are currently no reported studies of the long-term effects of altered behaviour in marine turtles.

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[470] Southwood, A., Fritsches, K., Brill, R. and Swimmer, Y. 2008. Sound, chemical and light detection in sea turtles and pelagic fishes: sensory-based approaches to bycatch reduction in longline fisheries. Endang Species Res 5: 225-238

[471] Budelmann, B. U. (1992a). Hearing in crustacea. In The Evolutionary Biology of Hearing (ed. D. B. Webster, R. R. Fay and A. N. Popper), pp. 131-140. New York: Springer-Verlag

[472] Budelmann, B. U. (1992b). Hearing in non-arthropod invertebrates. In The Evolutionary Biology of Hearing (ed. D. B. Webster, R. R. Fay and A. N. Popper), pp. 141-155. New York: Springer-Verlag.

[473] Southwood, A., Fritsches, K., Brill, R. and Swimmer, Y. 2008. Sound, chemical and light detection in sea turtles and pelagic fishes: sensory-based approaches to bycatch reduction in longline fisheries. Endang Species Res 5: 225-238

[474] LGL 2011. Environmental Assessment of a Marine Geophysical Survey by the R/V *Marcus G. Langseth* in the Central-Western Bering Sea, August 2011. LGL Report P1198-3

[475] O'Hara, J. and J.R. Wilcox. 1990. Avoidance responses of loggerhead turtles, *Caretta caretta*, to low frequency sound. Copeia 1990(2):564-567.

[476] McCauley RD, Duncan AJ, Penrose JD, et al. 2000. Marine seismic surveys – a study of environmental implications. APPEA J 40: 692–706

[477] Lenhardt, M. 2002. Sea turtle auditory behavior. J. Acoust. Soc. Amer. 112(5, Pt. 2):2314 (Abstract).

[478] Ibid

[479] McCauley RD, Duncan AJ, Penrose JD, et al. 2000. Marine seismic surveys – a study of environmental implications. APPEA J 40: 692–706

[480] DeRuiter, S.L. and Doukara, R.L 2010. Loggerhead turtles dive in response to airgun sound exposure. (ASA abstract)

[481] Samuel Y. et al., 2005. Underwater, low-frequency noise in a coastal sea turtle habitat. J. Acoust. Soc. Am. Volume 117, Issue 3, pp. 1465-1472

[482] Pendoley, K. 1997. Sea turtles and management of marine seismic programs in Western Australia. Petrol. Expl. Soc. Austral. J. 25:8-16.

MARINE INVERTEBRATES

Most marine invertebrates that are sensitive to sound are receptive to low frequencies by detecting the particle motion component of the sound field. Crustaceans appear to be most sensitive to sounds of less than 1 kHz[483] but able to detect up to 3 kHz in some species[484]. Cephalopods are sensitive to water movement stimuli in a range between <20 and 1500 Hz[485 486]. As well as being receptive to sound many invertebrates are also capable of producing sounds including species of barnacles, amphipods, shrimp, crabs, lobsters, mantis shrimps, sea urchins and squid[487 488 489 490]. In some species of invertebrates the sounds emitted are thought to be ecologically important in terms of acoustic communication between conspecifics[491]. It has been suggested that acoustic communication and perception in invertebrates might be related to as many functions as in marine vertebrates[492].

At the time of writing there are no reported research studies to determine the effects of a number of anthropogenic noise sources (pile driving, industrial activities and sonar) on marine invertebrates. In addition there are currently no reliable data available on hearing damage in invertebrates as a result of exposure to anthropogenic noise[493]. Sensitivity to low frequencies indicates that marine invertebrates are likely to be susceptible to sources such as shipping noise, offshore industrial activities (e.g., wind or tidal turbines) and seismic surveys.

The few studies that have been completed have primarily focussed on the impact of seismic surveys (air-gun arrays) on marine invertebrates, mainly crustaceans and cephalopods. A critical review of 20 studies completed up to 2004 found that only nine were quantitative[494] and within these the effects on marine invertebrate species were mixed (Table 2). The authors concluded that the lack of robust scientific evidence for the effects of seismic surveys on marine invertebrates meant that no clear conclusions could be made.

There are however a number of studies that should be mentioned. Firstly a significant increase in the strandings of giant squid in Spain during 2001 and 2003 coincided with the proximity of seismic survey

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[483] Budelmann, B. U. (1992a). Hearing in crustacea. In The Evolutionary Biology of Hearing (ed. D. B. Webster, R. R. Fay and A. N. Popper), pp. 131-140. New York: Springer-Verlag

[484] Lovell, J. M., M. M. Findlay, R. M. Moate, and H. Y. Yan. 2005. The hearing abilities of the prawn Palaemon serratus. Comp. Biochem. Physiol. A-Molecular & Integrative Physiology 140:89-100.

[485] Packard, A., Karlsen, H.E., and Sand, O. (1990). Low frequency hearing in cephalopods. J. Comp. Physiol. A., 166: 501-505.

[486] Hu, M.Y., H.Y. Yan, W-S Chung, J-C Shiao, and P-P Hwang. 2009. Acoustically evoked potentials in two cephalopods inferred using the auditory brainstem response (ABR) approach. Comp. Biochem. Physiol. A 153:278-283.

[487] Au, W.W.L. and K. Banks. 1998. The acoustics of snapping shrimp Synalpheus parneomeris in Kaneohe Bay. J. Acoust. Soc. Am. 103:41-47.

[488] Iversen, R.T.B., Perkins, P.J., Dionne, R.D., 1963. An indication of underwater sound production by squid. Nature 199, 250–251.

[489] Radford, C., Jeffs, A., Tindle, C., Montgomery, J.C., 2008. Resonating sea urchin skeletons create coastal choruses. Mar. Ecol. Prog. Ser. 362, 37–43.

[490] Staaterman, E.R., Clark, C.W., Gallagher, A.J., deVries, M.S., Claverie, T. and Patek, S.N. 2011. Rumbling in the benthos:acoustic ecology of the California mantis shrimp *Hemisquilla californiensis.* Aquat Biol 13: 97-105

[491] Ibid

[492] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[493] OSPAR Commission. 2009. Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

[494] Moriyasu et al., 2004. Effects of seismic and marine noise on invertebrates: A literature review. Canadian Science Advisory Secretariat. Research document 2004/126

vessels conducting air-gun arrays[495]. Pathological analysis of stranded squid showed the presence of lesions in tissues and organs leading to the suggestion that they were caused by excessive sound exposure from air guns[496]. Secondly a recent experimental study showed that moderately intense low frequency sound was responsible for the severe acoustic trauma and mortality in four species of cephalopod[497]. Lesions in the sensory epithelium and damaged sensory hair cells and nerve fibres were reported in each species. As relatively low levels of low-frequency sound and short exposure had induced severe acoustic trauma in cephalopods, it was suggested that there may be considerable effects of similar noise sources on these species in natural conditions over longer time periods[498].

Table 2. A summary of impacts of seismic surveys on marine invertebrates (after Moriyasu et al., 2004)

	Lethal / Physical	Physiological / Pathological	Behavioural	Catch rate
Negative	*Loligo vulgaris* *Chionoectes opilo (eggs)* *Chlamys islandicus* Sea urchins *Architeuthis dux*	*Bolinus brandaris*	*Alloteuthis sublata* *Sepioteuthis australs* *Architeuthis dux*	*Bolinus brandaris*
No impact	*Chionoectes opilo* *Mytilus edulis* *Gammarus locusta* *Crangon crangon*	*Chionoectes opilo*	*Chionoectes opilo*	*Crangon crangon* *Penaeus blebejus* *Nephrops norvegicus* *Illes coindetti* *Squilla mantis* *Paphia aurea* *Anadara inaequivalvis*

Table 2 indicates that marine invertebrates can also be affected by seismic surveys in terms of behaviour. Direct observation of squid exposed to air-gun sound showed a strong startle response involving ink ejection and rapid swimming at 174 dB re 1µPa rms and also avoidance behaviour[499].

Increased levels of background noise are likely to alter the acoustic environment of marine invertebrates. Low frequency anthropogenic noise may be masking acoustic communication in marine invertebrates such as crustaceans[500]. Masking of important acoustic cues used by invertebrates during larval orientation and settlement may also be a factor in the coastal zone and could lead to maladaptive behaviour that

[495] Guerra A, González AF, and Rocha F. 2004a. A review of records of giant squid in the north-eastern Atlantic and severe injuries in *Architeuthis dux* stranded after acoustic exploration. *ICES CM* 2004/CC: 29.
[496] Guerra A, González AF, Rocha F, et al. 2004b. Calamares gigantes varados. Víctimas de exploraciones acústicas. Investigación y Ciéncia 334: 35–37 (cited from Andre et al., 2011)
[497] Andre et al., 2011. Low-frequency sounds induce acoustic trauma in cephalopods. Front Ecol Environ 9: 489–493,
[498] Ibid
[499] McCauley RD, Duncan AJ, Penrose JD, et al. 2000. Marine seismic surveys – a study of environmental implications. APPEA J 40: 692–706.
[500] Staaterman, E.R., Clark, C.W., Gallagher, A.J., deVries, M.S., Claverie, T. and Patek, S.N. 2011. Rumbling in the benthos:acoustic ecology of the California mantis shrimp *Hemisquilla californiensis.* Aquat Biol 13: 97-105

reduces successful recruitment[501]. More subtle physiological changes could also occur in a noisy (stressful) environment. For example, brown shrimp exposed to increased background noise for up to three months demonstrated significant decreases in both growth and reproductive rates[502]. Shrimps were also more aggressive in the noisy tank, with increased mortality and decreased food intake. These are often regarded as symptoms of stress in vertebrates.

[501] Simpson SD, Radford AN, Tickle EJ, Meekan MG, Jeffs AG (2011) Adaptive Avoidance of Reef Noise. PLoS ONE 6(2): e16625. doi:10.1371/ journal.pone.0016625

[502] Lagardère, J.P. 1982. Effects of noise on growth and reproduction of *Crangon crangon* in rearing tanks. Mar. Biol. 71:177-186.

IV. MITIGATION AND MANAGEMENT OF UNDERWATER NOISE

This chapter reviews the existing measures and procedures in place to mitigate for the effects of underwater noise on marine organisms. Current guidelines for noise mitigation management have primarily been designed for marine mammals and particularly cetaceans. The limitations of mitigation guidance for naval exercises using active sonar and seismic surveying plus the development of standards for the measurement and control of underwater noise attributable to military and commercial operations will also be discussed. A number of management frameworks have been proposed. To date mitigation measures for underwater noise fall into two main categories: noise control at source and spatio-temporal restrictions of noise producing activities.

It should be noted here that the overall high level of uncertainty that currently exists regarding many of the effects of anthropogenic noise on marine fauna means that it is very important to use a precautionary approach when undertaking noise emitting activities in the marine environment. The application of the precautionary principle to the issue of marine noise has been discussed in some detail[503]. The precautionary approach may be inconvenient to those with narrow commercial interests, but precaution in the face of uncertainty is rational and is an approach that is now deeply embedded in the way that society operates[504]. Reducing uncertainty by increasing our knowledge and understanding of the issue will be the best guard against excessive precaution and over-regulation[505].

NOISE CONTROL AT SOURCE

One way to regulate noisy activities is to set criteria for noise exposure that should not be exceeded. For example, recently proposed sound exposure criteria for cetaceans and pinnipeds consist of both un-weighted peak pressures and weighted sound exposure levels which are an expression for the total energy of a sound wave[506]. These values are currently based on limited data sets with respect to noise induced injury and behavioural response in marine mammals. There have been similar attempts to define exposure criteria for fish[507], but none of the studies have been published in the peer reviewed literature[508]. A level of 180 dB re 1 μPa rms for cetaceans (both baleen and toothed whales) and 190 dB re 1 μPa rms for pinnipeds has been used as a generic exposure criterion in the U.S.[509] [510], although these have been criticised as being set too high[511]. There are no widely accepted exposure criteria for marine fish or other taxa.

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[503] Gillespie, A. 2007. The Precautionary Principle in the Twenty-First Century: A Case Study of Noise Pollution in the Ocean. The International Journal of Marine and Coastal Law 22(1): pp. 61-87

[504] Boyd, I.L., G. Frisk, E. Urban, P. Tyack, J. Ausubel, S. Seeyave, D. Cato, B. Southall, M. Weise, R. Andrew, T. Akamatsu, R. Dekeling, C. Erbe, D. Farmer, R. Gentry, T. Gross, A. Hawkins, F. Li, K. Metcalf, J.H. Miller, D. Moretti, C. Rodrigo, and T. Shinke. 2011. An International Quiet Ocean Experiment. *Oceanography* 24(2):174–181, doi:10.5670/oceanog.2011.37.

[505] Ibid

[506] Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R. Jr., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., and Tyack, P. (2007). Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33: 411-521.

[507] Popper, A.N., Carlson, T.J., Hawkins, A.D. and Southall, B.L. (2006). Interim criteria for injury of fish exposed to pile driving operations: a white paper (available at: http://www.wsdot.wa.gov/NR/rdonlyres/84A6313A-9297-42C9-BFA6750A691E1DB3/0/BA_PileDrivingInterimCriteria.pdf).

[508] Tasker at al., 2010 Tasker, M.L. Amundin M., Andre M., Hawkins A., Lang W., Merck T., Scholik-Schlomer A., Teilmann J., Thomsen F., Werner S. & Zakharia M. 2010. Marine Strategy Framework Directive. Task Group 11 Report. Underwater noise and other forms of energy. JRC and ICES.

[509] NMFS (National Marine Fisheries Service) 2003. Taking marine mammals incidental to conducting oil and gas exploration activities in the Gulf of Mexico. Federal Register, 68: 9991 – 9996.

[510] NOAA (National Oceanic and Atmospheric Administration). 2005. Endangered fish and wildlife; Notice of intent to prepare and environmental impact statement. Federal Register, 70: 1871-1875.

[511] Weilgart, L.S. 2007. The impacts of ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

Mitigation of the source can take the form of reducing the total amount of sound produced, by reducing power, duration and/or by reducing the number of times a system transmits sound. Where the species of concern has a well-defined hearing sensitivity, it may be possible to operate at frequencies where the animal's hearing is relatively insensitive.

SPATIO-TEMPORAL RESTRICTIONS

Noise levels experienced by marine animals during sound intensive activities can also be controlled by setting exclusion or safety zones. For example, the Joint Nature Conservation Committee (UK) recommends a marine mammal exclusion zone of 500m during the start of seismic surveys[512] while the Umweltbundesamt (Germany) recommends an exclusion zone of 750m around a pile driving site where a certain sound pressure level should not be exceeded. However, it remains unclear whether or not safety zones are effective in protecting marine animals from excessive sound exposure. For example, it is not always guaranteed that sound pressure drops monotonically with increasing distance. Exclusion zone validity is also questionable if exposure levels in the field are not measured during the sound producing operation. More subtle effects such as masking and behavioral responses are also possible beyond the recommended exclusion zone for some marine animals[513].

Exclusion of the noisy activity through the use of spatial restrictions such as statutory marine protected areas (MPAs) has been described as the most effective means of protecting cetaceans and their habitats from the cumulative and synergistic effects of noise as well as from other anthropogenic stressors[514] [515]. Enforcement of permanent or temporary exclusion zones such as MPAs requires effective and constant monitoring, control and surveillance[516]. The use of spatio-temporal restrictions (STRs) to protect marine mammals and other taxa from noise pollution and other stressors has been strongly endorsed with the proposal of a conceptual framework for STR implementation[517]. Geographical and seasonal restrictions to avoid the ensonification of sensitive species and habitats are also known to be a highly effective mitigation measure[518] and can be part of an STR approach within marine spatial planning. Sound-producing activities can be scheduled to avoid areas or times that sensitive marine mammals and other species use for susceptible activities such as mating, breeding, feeding, or migration. There is however a difference between human activities producing noise as an unwanted side effect (e.g., shipping and pile driving) and activities deliberately emitting sounds (e.g., seismic surveys) for specific goals. Noise from the former can be reduced by using mitigation tools without impairing their main mission objectives. The latter are potentially more difficult to reduce their sound emission and may also be less flexible on a temporal scale.

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[512] Joint Nature Conservation Committee- JNCC-(2004). Guidelines for minimising acoustic disturbance to marine mammals from seismic surveys. JNCC, Aberdeen (www.jncc.gov.uk).

[513] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[514] Sascha K. Hooker & Leah R. Gerber. 2004. Marine Reserves as a Tool for Ecosystem-Based Management: The Potential Importance of Megafauna. 54 BioScience 27 .

[515] Weilgart, L.S. 2006. Managing Noise through Marine Protected Areas around Global Hot Spots. IWC Scientific Committee (SC/58/E25).

[516] André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution.Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029. www.lab.upc.es .

[517] Agardy, T., Aguilar, N., Cañadas, A., Engel, M., Frantzis, A., Hatch, L., Hoyt, E., Kaschner, K., LaBrecque, E., Martin, V., Notarbartolo di Sciara, G., Pavan, G., Servidio, A., Smith, B., Wang, J., Weilgart, L., Wintle, B. and Wright, A. 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise. Report of the Scientific Workshop. 44 pages

[518] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

Proposed mitigation measures or techniques

The development of ‘warning signals’ for marine mammals has been proposed[519] but there has been little development and testing for this to date. Some studies have shown that right whales (*Eubalaena* sp.) show strong responses to signals designed to alert them even though in this case one response was to surface and therefore be potentially more susceptible to ship collisions[520]. Very little is known of responses to warning signals by other marine species[521]. Acoustic harassment devices have been used for both seals and harbour porpoises and have proven to be effective in scaring the animals away from the source at close ranges[522] [523] [524], although habituation is possible[525]. However, since these devices deliberately disturb the receiver, their application needs to be considered from a conservational viewpoint. ‘Whale-finding’ sonar has been identified as the mitigation measure of the future[526]. These are high-frequency low-power sonars and therefore have a limited detection range (~ 2 km). Another suggestion is the use of sonar systems currently deployed in commercial fisheries (e.g., ‘tuna finding’ sonar) for the initial detection of marine mammals within an area. Adding more noise to the marine environment as a mitigation measure for noise remains controversial.

MITIGATION MEASURES FOR SPECIFIC NOISE GENERATING ACTIVITIES

Marine construction and industrial activities

One of the greatest sources of noise pollution from marine industrial activities is pile driving. There are currently several options available to reduce the sound impacts of pile driving at source[527] [528]:

- Enclosing the ramming pile with acoustically-isolated material (mantling) can decrease the source level by 5–25 dB, with higher frequencies more affected than lower ones. Further research is required to establish whether this will have a reduction in the far field. Mantling appears to be very promising but has so far only been tested in a relatively short pile.
- Installing an air-bubble curtain around the pile will result in a decrease of up to 20 dB, depending on frequency[529]. However, air bubble curtains are very expensive and might only be effective in relatively shallow water.

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[519] National Research Council 1994. Low-frequency sound and marine mammals: current knowledge and research needs. National Academy Press, Washington, D. C. 92pp.

[520] Nowacek, D. P., Johnson, M. P. and Tyack, P. L. 2004. Right whales ignore ships but respond to alarm stimuli. Proceedings of the Royal Society B: Biological Sciences 271: 227–231.

[521] Aguilar de Soto, N., Johnson, M., Madsen, P., Bocconcelli, A., Tyack, P, Borsani, F. Does shipping noise affect the foraging behaviour of Cuvier’s beaked whale (Ziphius cavisrostris)? Marine Mammal Science 22(3):690-699

[522] Yurk, H. and Trites, A.W. (2000). Experimental attempts to reduce predation by harbor seals on out-migrating juvenile salmonids. Transactions of the American Fisheries Society 129, 1360-1366.

[523] Culik, B.M., Koschinski, S., Tregenza, N. and Ellis, G.M. (2001). Reactions of harbour porpoises *Phocoena phocoena* and herring *Clupea harengus* to acoustic alarms. Marine Ecology Progress Series 211, 255-260.

[524] Cox, T.M., Read, A.J., Solow, A. and Tregenza, N. (2001). Will harbour porpoises habituate to pingers?. Journal of Cetacean Research and Management. 3, 81-86.

[525] National Research Council 1994. Low-frequency sound and marine mammals: current knowledge and research needs. National Academy Press, Washington, D. C. 92pp

[526] Gentry, R. L. 2004. Mitigation measures for use with military sonar. *In*: Proceedings of the workshop on active sonar and cetaceans, pp. 66–69. Ed. by P. G. H. Evans and L. A. Miller. European Cetacean Society Newsletter No 42.

[527] Nehls, G., Betke, K., Eckelmann, S., and Ros, M. (2007). Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore windfarms. COWRIE Ltd, Newbury, U.K.

[528] ASCOBANS 2009: Sixth Meeting of the Parties, Res. 2, “Adverse Effects of Underwater Noise on Marine Mammals during Offshore Construction Activities for Renewable Energy Production”

- Applying a soft-start/ramp-up procedure by slowly increasing the energy of the emitted sound). Soft-start procedures are theoretically promising but their effect has not been tested to a large degree. Ramping-up might also make it more difficult for cetaceans and seals to localise the sound source[530].
- The use of acoustic harassment devices for marine mammals or fish may be effective in scaring the animals away from the source of a potential impact[531]. Their effective deterrent zone can be less than the noise impact zone so several devices may need to be deployed at different distances from the construction site.
- Precautionary mitigation measures can include not carrying out pile driving in confined areas in close proximity to migrating fish and turtles, or during peak feeding or breeding season for marine mammals
- Alternative methods such as hydraulic pile driving may prove favourable as this method results in lower noise emissions which are close to the background noise level at sea (<100 dB re 1μPa).
- Delaying the start of or ceasing piling if turtles or marine mammals are detected (visually or acoustically) close to the source may also be effective in mitigating close-range effects[532].

Shipping

The scientific understanding of exactly how shipping noise impacts marine life, particularly regarding behavioural impacts, is currently limited[533]. However, the acoustic communication functions of many species may be negatively impacted by noise exposure, depending upon conditions and ambient noise levels in some biologically important areas[534] [535]. Reducing the overall noise output from marine vessels is likely to have demonstrable positive outcomes for acoustic communication, navigation, foraging efficiency, predator avoidance capabilities and noise induced stress. Unlike persistent forms of pollution, noise does not linger in the marine environment after it is introduced. Vessel-quieting technologies and/or operational strategies therefore have the potential to provide immediate benefits for marine animals that rely on sound.

Quieting technology for both surface and sub-surface military vessels to reduce their acoustic signature has been in use for some time[536]. Some of the understanding and many of the concepts of noise reduction

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529 Würsig, B., Green, C.R. Jr., and Jefferson, T.A. (2000). Development of an air bubble curtain to reduce underwater noise of percussive piling. Mar. Environ. Res. 49, 79-93.

530 Richardson, W. J., Greene, C. R., Malme, C. I., & Thomson, D. H. (Eds.). 1995. Marine mammals and noise (Academic Press, New York), 576 pp.

531 Yurk, H. & Trites, A.W. 2000. Experimental attempts to reduce predation by harbour seals (Phoca vitulina) on out-migrating juvenile salmonids. Transactions of the American Fisheries Society 129: 1360-1366

532 Evans, P.G.H. and Hammond, P.S. (2004) Monitoring Cetaceans in European Waters. Mammal Review, 34: 131-156.

533 OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

534 Hatch, L. T., C. W. Clark, R. Merrick, S. Van Parijs, D. Ponirakis, K. Schwehr, M. Thompson, and D. Wiley. (2008). Characterizing the relative contributions of large vessels to total ocean noise fields: a case study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. Environmental Management (online – see: http://www.springerlink.com/content/u1p51226016240lp/fulltext.pdf)

535 Wright, A. J., N. Aguilar Soto, A. L. Baldwin, M. Bateson, C. Beale, C. Clark, T. Deak, E. F. Edwards, A. Fernández, A. Godinho, L. Hatch, A. Kakuschke, D. Lusseau, D. Martineau, L.M. Romero, L. Weilgart, B. Wintle, G. Notarbartolo-di-Sciara, and V. Martin. 2008. Do marine mammals experience stress related to anthropogenic noise? International Journal of Comparative Psychology, 20: 274-316.

536 McDonald, M. A., J. A. Hildebrand, and S. M. Wiggins. 2006. Increases in deep ocean ambient noise in the northeast Pacific west of San Nicholas Island, California. Journal of the Acoustic Society of America 120, 711-718.

engineering in military vessels can be tailored to the merchant fleet[537]. Commercial applications of ship quieting technology are advancing, with many of the associated technologies focusing on aspects of the propeller or other components of the propulsion systems. There may also be benefits in efficiency and reduced fuel consumption associated with reduced propeller cavitation, which will also reduce the overall radiated noise signature[538]. Minimizing propeller cavitation across the range of operating conditions should be the priority for larger vessels, given that other on-board noise sources will likely be overwhelmed by cavitation noise[539]. A range of actions have recently been identified to reduce ship noise including the development and implementation of noise limits and guidelines for individual ships that are considered before and during construction as well as actions that will help to identify and develop engineering measures for reduction of propeller and machinery noise[540].

Efforts to reduce structure-borne noise may be facilitated by advances in propulsion systems. The use of devices termed 'skysails' can result in the saving of up to 35% in fuel costs and cut noise levels accordingly as there is less engine demand. Skysails are attached to the bow of the ship and harness the wind in assisting the ship's propulsion[541]. Operational measures such as routing and speed restrictions could also have positive outcomes for ambient noise reduction in some areas. The relative costs and environmental benefits of either technological or operational mitigation measures related to vessel noise output are not well-known. One estimate for the quieting of an oil tanker was $2.7 million[542].

Working with the shipping industry is an essential part of the mitigation process along with reaching international agreements on noise emission levels. At a workshop in 2008 several industry leaders agreed that vessel noise is a global issue and set a goal of freezing noise levels within 10 years and then reducing them by several-fold within 30 years[543]. Recently, the United States submitted a proposal to the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) to explicitly consider this international matter and consider a global strategy[544]. The issue has been taken up by the IMO and progress is being made on exploring technical options to minimize the introduction of incidental noise into the marine environment from commercial shipping and, in particular, develop voluntary technical guidelines for ship-quieting technologies as well as potential navigation and operational practices.

In 2010, following a thorough assessment of the existing design and operational modifications and possibilities potentially relevant in the reduction of incidental noise produced by large vessels, MEPC agreed that:

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537 Wright, A.J. (ed) 2008. International Workshop on Shipping Noise and Marine Mammals, Hamburg, Germany, 21st-24th April 2008. Okeanos - Foundation for the Sea, Auf der Marienhohe 15, D-64297 Darmstadt. 33+v p. http://www.okeanos-foundation.org/assets/Uploads/Hamburg-shipping-report-2.pdf

538 OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

539 Southall, B. L., A. E. Bowles, William T. Ellison, J. J., J. J. Finneran, R. L. Gentry, C. R. G. Jr., D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack. 2008. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals 33:1-521.

540 Wright, A.J. (ed) 2008. International Workshop on Shipping Noise and Marine Mammals, Hamburg, Germany, 21st-24th April 2008. Okeanos - Foundation for the Sea, Auf der Marienhohe 15, D-64297 Darmstadt. 33+v p. http://www.okeanos-foundation.org/assets/Uploads/Hamburg-shipping-report-2.pdf

541 André M, Morell M, Mas A, et al. 2010. Best practices in management, assessment and control of underwater noise pollution. Laboratory of Applied Bioacoustics, Technical University of Catalonia, CONAT150113NS2008029.

542 Malakoffv, D. 2010. A push for quieter ships. Science 328. 1502 – 1503.

543 Ibid

544 United States Government (U.S.G.). 2008. Minimizing the introduction of incidental noise from commercial shipping operations in the the marine environment to reduce potential adverse impacts on marine life. Submitted to the Marine Environment Protection Committee of the International Maritime Organization, 58th session, agenda item 19.

1. the propeller is the main source for ship-generated underwater noise;
2. non-binding, technical guidelines and consideration of solutions to reduce the incidental introduction of underwater noise from commercial shipping would, in turn, reduce potential adverse impacts to marine life. Accordingly, the most plausible design and/or retrofit options (propulsion, hull design, onboard machinery and operational modifications) should be assessed by naval architects and engineers;
3. depending on the practicality/cost of noise mitigation measures, possible operational modifications should be considered for both new and existing vessels; and,
4. future research programmes should focus on the propeller and the relationship between cavitation and the cause of underwater sonic energy.

Currently the matter is before IMO's Design and Equipment Sub-Committee, which aims to develop the technical guidelines to address the issue on noise from commercial shipping and its adverse impacts on marine life, with a view to providing advice to MEPC in 2012-2013.

Military active sonar

Almost all of the mitigation measures conducted by the military are focused on marine mammals. Mitigation strategies range from the control of noise at source, to the complete cessation of the sonar activity. Simulations are used for training personnel in sonar operations but cannot completely remove the need for training at-sea.

The likelihood of a marine mammal being in the area prior to the commencement of a sonar transmission is moderate unless there is a large degree of overlap between the location of important habitats or migration routes and areas of sonar usage. There are several mitigation measures that might be effective in preventing injury through the direct effects of sonar. Firstly, vessels can avoid areas of known marine mammal abundance. If marine mammals are detected close to the source then regulation of the sonar transmission can be implemented. Detection of marine animals in the vicinity is therefore an important part of the mitigation process and is conducted by the use of marine mammal observers (MMOs) and either passive or active acoustic monitoring systems (PAM or AAM). MMOs are trained observers who aim to visually detect and identify marine mammals, at distances of up to 500m during daylight hours. Use of MMOs is mandatory on UK, German and Norwegian naval ships operating active sonar. The effectiveness of MMOs especially in conditions of poor visibility such as poor sea state, fog, and darkness, and for deep-diving species that are seldom seen at the surface, is likely limited.

Both passive and active acoustic monitoring can be used to detect marine mammals. Passive monitoring relies on marine animals to produce sound (and for those sounds to be recognised) and thus is not reliable for all species at all times. AAM systems can detect non-vocalizing animals such as marine mammals or fish, although often only at closer ranges than passive monitoring. Active acoustic monitoring can also estimate the range of targets more easily than passive monitoring. AAM is relatively undeveloped compared to PAM for detecting marine mammals and it adds another type of anthropogenic noise to the marine environment. Both systems can be installed on remotely operated or autonomous vehicles or from buoys or bottom-mounted hydrophones to provide a sweep of a wider area or for a longer time period than would be possible from a single vessel.

Passive or active acoustic monitoring offers the means to assess a large area of ocean when studying beaked whales in order to improve mitigation measures. If the lethal effects previously observed in beaked whales are due to a behavioural response to a lower level of active sonar sound and not to the direct physical effects of the higher level of sound itself then the exclusion zone during sonar transmissions needs to be large enough to ensure such a potentially lethal behavioural response does not occur.

Mitigation guidance during naval exercises

Guidance for mitigation is developed individually by a country for use by their own Navy, and, on the whole, navies self-regulate and set their own mitigation strategies[545]. Naval mitigation measures for active sonar exercises were recently reviewed in detail[546] but may have been updated since. Access to military mitigation guidelines can be challenging and it is likely that some guidance is not publicly available[547]. The mitigation guidance used during naval exercises usually has three main components[548]:

1. time/area planning (of exercises/active sonar use) to avoid marine mammals;
2. implementation of operational procedures (e.g., 'soft start'); and
3. monitoring of animals for the purpose of maintaining an 'exclusion zone'.

A summary of the guidance implemented by a number of Navies up to 2008 (Table 3) indicates that there is considerable variation in the guidelines followed by different countries and only one measure (use of an exclusion zone) is implemented by all those listed. A few of the key mitigation measures and their limitations will be mentioned here. Details of other measures are available in the review[549].

Avoidance of sensitive areas

Most naval guidance loosely defines sensitive areas as breeding, feeding or migration habitat for marine mammals, and/or focuses on specific measures for beaked whales. While many guidelines request more stringent mitigation procedures within such areas and suggest planning surveys to avoid sensitive times or areas, there is little rigorous definition of these areas and how they should influence naval exercises. The Norwegian navy (RNoN) guidelines include avoiding areas and periods of high marine mammal density and known beaked whale habitats, as well as avoiding whale watching areas, areas of intense fishing and whaling activities, and some fish spawning grounds and maintenance of a 200 m buffer around aquaculture facilities[550]. Only a few of the guidelines imposed a buffer zone around sensitive areas.

Soft start

A soft start (or ''ramp-up'') is a technical term for the gradual introduction of the sound source, and aims to provide any animals in the vicinity of the source with an opportunity to move away. However the effectiveness of the technique has not been proven. Soft starts are compulsory in most naval exercises with the exception of a few. During active sonar operation, soft start involves a gradual build-up of sound level and/or pulse duration over time, with the aim of warning marine mammals and allowing them to depart from the area before the sonar pulses reach peak amplitude and/or duration. The soft start process can vary in length from 15 to 30 minutes and breaks in transmission can also vary in length before a soft start is required again. For example a break of 30 minutes will trigger the need for a soft start for NATO exercises whilst the same trigger for the Canadian navy is a two hour gap.

Visual detection

[545] Glassborow, J., 2006. Sensors and sensibilities: navies factor mammals into sonar use. Janes Navy international, September 2006. p. 28–32

[546] Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477.

[547] Ibid

[548] Ibid

[549] Ibid

[550] Ibid

Apart from external factors such as darkness or adverse weather conditions, the efficacy of visual detection depends on a number of variables including the number of marine mammal observers (MMOs) present, their experience, the regularity of observation breaks (i.e. concentration span), their dedication, objectivity (crew member or independent third-party), and enthusiasm and lastly their level of training[551]. There does not appear to be a standard training programme for MMOs[552] or a requirement that they are independent and civilian trained[553]. Aerial surveillance is required in some parts of the U.S. in addition to MMOs. For major exercises off California, a federal court required the U.S. Navy to conduct dedicated aerial monitoring for one hour before the start of sonar use and to continue monitoring during each exercise[554].

Exclusion zones

The exclusion zone (or 'safety zone') is usually defined as the radius around the sonar source within which real-time mitigation measures are implemented if animals are detected. Exclusion zones vary considerably in size and may be larger for naval sonar than for seismic surveying, where a 500 m exclusion zone is standard. The zone radius varies according to the type of marine mammal (e.g., toothed, baleen or beaked whale), source type (impulsive or coherent) and also between navies, ranging between 1500 and 4000 m[555].

Mitigation measures for marine fish

Only the Royal Norwegian Navy has implemented mitigation measures for fish; which are subject to revision depending upon ongoing studies on sonar effects on fish. During the planning of exercises involving transmissions below 5 kHz, planners should avoid spawning grounds, and areas with large numbers or intense fishing of herring and brisling (small herring). As a general precaution, a safety zone of 200m from all fish farms and all fishing vessels actively involved in fishing is also implemented. In addition some restrictions on transmission of certain waveforms and frequencies are required, as signals at these frequencies can match the swim bladder resonance of juvenile herring leading to damage[556].

Seismic surveys

A range of mitigation measures, similar to those used for active sonar, are applied either singly or in combination to reduce the potential impacts of marine seismic surveys on marine life. The methods employed include: geographical and/or seasonal restrictions, source reduction or optimisation, the use of buffer zones, surveillance of buffer zones by visual, acoustic or other means, and "ramp-up" or "soft-start" techniques.

Source reduction

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[551] Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27.

[552] Parsons, E.C.M., Dolman, S.J., Jasny, M., Rose, N.A., Simmonds, M.P., Wright, A.J. 2009. A critique of the UK's JNCC Seismic Survey Guidelines for minimising acoustic disturbance to marine mammals: best practise? Marine Pollution Bulletin 58 pp. 643 651.

[553] Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477.

[554] Ibid

[555] Ibid

[556] Jørgensen, R., Olsen, K. K., Falk-Petersen, I.-B. and Kanapthippilai, P. 2005. Investigations of potential effects of low frequency sonar signals on survival, development and behaviour of fish larvae and juveniles. Norwegian College of Fishery Science University of Tromsø. 49pp.

Two international conservation agreements (ASCOBANS[557] and ACCOBAMS[558]) and a number of advisory bodies such as the California Coastal Commission[559] have suggested limits on source levels used during seismic surveys and have proposed measures including the use of lowest practicable power levels, reduction of unnecessary high intensity sound[560], array optimisation or avoidance of sources of 'unnecessarily' high energy. For example, the Joint Nature Conservation Committee (JNCC) of the UK calls for operators to reduce unnecessary high-intensity sound produced by air guns or other acoustic energy sources. These guidelines have been incorporated into relevant permits for oil and gas seismic surveys within the UK.

Geographical and seasonal restrictions

The most effective and straightforward mitigation measures are geographical and seasonal restrictions to avoid ensonification of sensitive species and habitats. This approach is taken in Australia[561], Brazil[562], the UK[563] and Norway[564] [565]. The IWC Scientific Committee has called for seismic surveys to be arranged spatial-temporally so that eventual acoustic impacts are reduced[566]. The IUCN recommends that member governments work through domestic and international legislation to consider restrictions for sound in their management guidelines for Marine Protected Areas (MPAs)[567]. In Norway, seasonal restrictions on seismic surveys may be imposed in specific areas[568], or included in the license conditions[569]. Prior to each seismic survey the Norwegian Institute of Marine Research undertakes a biological evaluation and provides recommendation. More regions need to clearly define and identify sensitive areas of their marine environment both spatially and temporally to then prevent or severely restrict intense sound producing activities to protect marine biodiversity.

Exclusion zones

Animals outside this zone are presumed not to be exposed to harmful levels of sound. The radius of exclusion zones for seismic surveys is usually defined by the regulatory agency or promoted by other

[557] ASCOBANS 2006: Fifth Meeting of the Parties, Res. 4, "Adverse Effects of Sound, Vessels and Other Forms of Disturbance on Small Cetaceans

[558] ACCOBAMS 2004: Second Meeting of Parties, Res. 2.16, "Assessment and Impact Assessment of Man Made Noise."

[559] California Coastal Commission 2002: Consistency Determination. No. CD-14-02, USGS, 2002 Southern California seismic survey.

[560] JNCC-Joint Nature Conservation Committee. 2003: JNCC Report No. 323, C.J. Stone, The Effects of Seismic Activity on Marine Mammals in UK Waters: 1998-2000.

[561] Environment Australia 2001: Guidelines on the application of the Environment Protection and Biodiversity Conservation Act to interactions between offshore seismic operations and larger cetaceans, ISBN 064254784X (Oct. 2001).

[562] Brazil CONAMA. 2004: National Environment Council Res. 305 (July 2004).

[563] ASCOBANS 2003: Fourth Meeting of Parties, Res. 5, "Effects of Noise and of Vessels".

[564] Bjørke, H., Dalen, J., Bakkeplass, K., Hansen, K., Rey, L. 1991. Seismic activities' accessibility in relation to vulnerable fish resources. (In Norwegian). Institute of Marine Research, HELP Report no 38, 1991, Bergen, Norway: 119 pp.

[565] Dalen, J., Ona, E., Vold Soldal, A. & Sætre, R. 1996: Offshore seismic investigations: An evaluation of consequences for fish and fisheries. Institute of Marine Research, Bergen, Norway. Fisken og havet No 9 - 1996. 26 pp.

[566] IWC - International Whaling Commission. 2004: Report of the Scientific Committee, at 12.2.5, pp. 37-39 and Annex K – Report of the Standing Working Group on Environmental Concerns. 267-275 and 282-289. Journal of Cetacean Research and Management. Vol. 7 Suppl. April 2005, ISSN 1561-0713.

[567] IUCN-World Conservation Union. 2004: Resolution 3.068 Undersea noise pollution (Nov. 2004).

[568] Bjørke, H., Dalen, J., Bakkeplass, K., Hansen, K., Rey, L. 1991. Seismic activities' accessibility in relation to vulnerable fish resources. (In Norwegian). Institute of Marine Research, HELP Report no 38, 1991, Bergen, Norway: 119 pp.

[569] Anon. 1985: Permission for investigation for petroleum. The Norwegian Petroleum Directorate: p 12-16 in Fishery-proficient person aboard seismic vessel. The Directorate of Fisheries, Bergen, 1992.

groups[570], and can range from 500m[571] to in excess of 1km[572]. The presence of animals within the exclusion zone may require stopping an operation or delaying its start-up.

Visual surveillance

Monitoring exclusion zones is carried out by specialist marine mammal observers (MMOs). These observers scan the zone before and during start-up and also through the period of the survey, recording and subsequently reporting sightings of animals both within and beyond the safety zone[573]. The ability to monitor zones is determined by sea state and practical visibility. However, the ability to monitor certain species is limited even within small radii[574]. The probability of visually detecting beaked whales is 1-2% at most due to their long dives[575]. Visual surveillance data can provide information that may aid understanding of behavioural reactions of different species. IWC[576] has made the following recommendations:

- Continuous acoustic monitoring of critical habitats on sufficient temporal and spatial scales in relation to pre- and post-seismic activity.
- Independent monitoring of critical habitats (from survey vessel and independent platforms) to evaluate displacement from critical habitat and/or disruption of important cetacean behaviours in the critical habitat.
- Increased effort to monitor strandings that may coincide with the activity.

Visual surveillance is frequently supplemented by acoustic and other electronic techniques. These include both passive and active acoustic monitoring, as well as radar and infrared scanning[577]. The PAM system usually employed during seismic surveys is the towed array, since air guns are mobile and require a moveable mitigation system.

Soft Start/Ramp-up techniques

Soft starts are commonly used in seismic surveys around the world. In most regions a soft-start is required to be at least 20 minutes before full power is reached and a survey line commenced[578]. The upper limit is generally 30 minutes with some regions going up to 40-45 minutes.

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[570] IUCN-World Conservation Union. 2006: Report of the interim independent scientists group (IISG) on mitigation measures to protect Western gray whales during Sakhalin II construction operations in 2006. Workshop convened by the IUCN, Vancouver, British Columbia, 3–5 April 2006.

[571] JNCC-Joint Nature Conservation Committee. 2003: JNCC Report No. 323, C.J. Stone, The Effects of Seismic Activity on Marine Mammals in UK Waters: 1998-2000.

[572] Environment Australia 2001: Guidelines on the application of the Environment Protection and Biodiversity Conservation Act to interactions between offshore seismic operations and larger cetaceans, ISBN 064254784X (Oct. 2001).

[573] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[574] Barlow, J. and Gisiner, R. 2006. Mitigating, monitoring and assessing the effects of anthropogenic sound on beaked whales. Journal of Cetacean Research and Management, 7: 239–249.

[575] US-MMC 2004: Beaked Whale Technical Workshop Summary. April 13-16, 2004, Baltimore, USA.

[576] IWC. 2004. Report of the Scientific Committee, at 12.2.5, pp. 37-39 and Annex K – Report of the Standing Working Group on Environmental Concerns. 267-275 and 282-289. Journal of Cetacean Research and Management. Vol. 7 Suppl. April 2005, ISSN 1561-0713.

[577] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[578] Ibid

Limitations to mitigation techniques for active sonar exercises and seismic surveys

Current limitations of the mitigation techniques used for naval sonar exercises and seismic surveys have been thoroughly reviewed in the literature recently[579] [580]. A summary of the limitations identified for both sources of anthropogenic noise in the marine environment are provided in Table 4. It is clear that the guidance and execution of mitigation measures for both sound sources are not completely effective in preventing marine mammals (and most likely other taxa) from being exposed to damaging or disturbing levels on some occasions.

Many of the current guidelines in place are out dated or are based on inadequate data as highlighted by a number of authorities including United States Commission on Ocean Policy in its Ocean Blueprint for the 21st Century[581]. In addition, particular research gaps identified by the Scientific Committee of the IWC[582], ICES[583], and the Parties to ACCOBAMS[584], highlight the current limited effectiveness of existing mitigation measures. As a result, before adequate mitigation can be enforced it will be necessary to address some of the pressing research questions, then critically review current mitigation guidelines and update them accordingly.

[579] Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27.

[580] Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477.

[581] United States Commission on Ocean Policy. (2005). Ocean Blueprint for the 21st Century (National Technical Information Service, Washington). 315–316.

[582] IWC Scientific Committee, (2004) IWC/56/Rep I. Section 12.2.5.

[583] The International Council for the Exploration of the Sea (ICES) (2005) Report of the Ad Hoc Group on the Impact of Sonar on Cetaceans. ICES CM 2005/ACE:06. At page 47. See ICES Advisory Committee on Ecosystems, n. 1 above, at 47– 49.

[584] Resolution 2.16. Assessment And Impact Assessment Of Man-Made Noise. Report of the Second Meeting of the Parties to ACCOBAMS (UNEP/CMS).

Table 3. Marine mammal guidance implemented during naval exercises (after Dolman et al., 2009)

Mitigation	Australia	Canada	France	Italy	Norway	NURC	Canary Islands	UK	Hawaii	SoCAL	RIMPAC 2006	NDE I, 2006	NDE II, 2007
Selection of area	Y	N	Y	Y	Y	Y	N	Y	N	N	N	N	Y
Buffer zone	Y	N	N	Y	N	N	N	N	N	N	N	N	N
Coastal exclusion	Y	N	N	N	N	N	Y	N	Y	Y	Y	Y	N
Det sys/database	Y	Y	N	Y	Y	Y	N	Y	N	N	N	N	N
Pre/post ded. Survey	Y	N	Y	Y	Y	Y	N/R	Y	Y	Y	Y	Y	Y
Increased lookout	Y	Y	Y	Y	Y	Y	N/R	Y	Y	Y	Y	Y	Y
Trained observers	N	N	N	N	N	N	N/R	Y	Y	Y	Y	Y	Y
Weather/sightability	Y	Y	N	N	N	Y	N/R	Y	Y	N	Y	Y	Y
PAM	Y	Y	Y	Y	Y	Y	N/R	Y	Y	Y	N	Y	Y
Other monitoring	Y	N	N	N	N	Y	N/R	N	Y	Y	Y	Y	Y
Min source required	N	Y	N	N	Y	Y	N/R	N	Y	Y	Y	Y	Y
Prop. conditions	N	Y	N	N	N	Y	N/R	N	Y	Y	Y	Y	Y
Soft start/ramp-up	N	Y	Y	Y	Y	Y	N/R	N	Y	N	N	N	N
Delay if cet obs'd	N	N	N	N	Y	Y	N/R	N	N	N	N	N	N
Repeat ramp-up	N	N	N	Y	Y	Y	N/R	N	N	N	N	N	N
Pwr dn if cet det	N	N	Y	N	Y	Y	N/R	Y	Y	Y	Y	Y	Y
Sonar off if cet det	Y	Y	Y	N	Y	Y	N/R	Y	Y	Y	Y	Y	Y
Exclusion zone	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
All marine mammals	N	Y	Y	Y	Y	N	N/R	Y	Y	Y	Y	Y	Y
Cow/calf pairs	Y	N	N	N	N	N	N/R	N	Y	Y	N	N	N
Other species	Y	N	N	N	Y	N	N/R	Y	N	N	N	Y	N
Stranding response	N	Y	N	N	N	Y	N/R	N	Y	N	Y	Y	Y
Reporting	Y	Y	N	N	N	Y	N/R	Y	Y	Y	Y	Y	Y
EIA	Y	N	N	N	N	Y	N/R	Y	Y	Y	Y	N	N
Excl. of spec. area	Y	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y
Research	N	N	N	N	Y	N	N	N	Y	Y	N	N	N

Y, yes; N, no; N/R, not required; NDE, US National Defence Exemption.

Some national guidelines[585] for marine mammal noise mitigation during seismic surveys have come under significant criticism[586] [587]. The JNCC guidelines were the first national guidelines to be developed and have become the unofficial standard of international mitigation measures for noise management during seismic surveys. However, only a few features of these measures have a firm scientific basis. On the whole, existing guidelines do not offer adequate protection to marine mammals, given the complex propagation of air-gun pulses; the difficulty of monitoring in particular the smaller, cryptic, and/or deep-diving species, such as beaked whales and porpoises; limitations in monitoring requirements; lack of baseline data; and other biological and acoustical complications or unknowns[588]. Current guidelines offer a 'common sense' approach to noise mitigation, but should be updated regularly according to the most recent research findings. Broader measures are needed to ensure adequate species protection and to address data gaps. There have been calls for a consistent global set of guidelines for industrial-induced marine noise[589].

Enforcement of existing mitigation measures can also be an issue. There is a lack of onboard monitoring (or feedback system) of the effectiveness of guidelines, no evaluation of the mitigation procedures and no repercussions for operators that fail to comply with the guidelines[590].

There are also areas both within and beyond national jurisdiction that are not subject to mitigation measures for seismic surveys. In fact the majority of the world's oceans are open to seismic surveying and other similar noise producing works without any marine mammal mitigation procedures in place[591]. However, the legislation that a State may have adopted to regulate underwater noise will apply to the vessels flying its flag, independent of where they carry out their activities (unless this is specified in the legislation itself). Some of the regional guidelines are also rather selective regarding inclusion of their own waters, for example in most of the Gulf of Mexico the MMO guidelines apply only to water depths greater than 200m[592] providing no protection for marine mammals in shelf waters. In regions where no statutory legislation exists for the protection of marine mammals or other species, many surveys occur within sensitive habitats without any consideration of marine faunal species which they may affect[593].

585 JNCC, 2004. Guidelines for minimizing acoustic disturbance to marine mammals from seismic surveys. Joint Nature Conservation Committee, Peterborough. http://www.jncc.gov.uk/pdf/Seismic_survey_guidelines_200404.pdf

586 Parsons, E. C. M., Dolman, S. J., Wright, A. J., Rose, N. A. and Simmonds, M. P. 2009. A critique of the UK's JNCC Seismic Survey Guidelines for minimising acoustic disturbance to marine mammals: best practise? Mar. Poll. Bull.. 58: 643-651

587 http://whitelab.biology.dal.ca/lw/Canadian_Seismic_Comments.doc.

588 Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27.

589 Compton, R., Goodwin, L., Handy, R., Abbott, V (2008) A critical examination of worldwide guidelines for minimising the disturbance to marine mammals during seismic surveys. Marine Policy 32, 255–262.

590 Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27.

591 Ibid

592 Smith, J.G. & M.R. Jenkerson. Acquiring and Processing Marine Vibrator Data in the Transition Zone. Mobil Exploration and Producing Technical Centre (1998).

593 Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27.

The mitigation guidelines governing the use of active sonar have come under similar criticism[594]. Furthermore, despite the range of mitigation measures in place, a large amount of associated naval operations are conducted with no or minimal mitigation. Another limitation is that ships carrying mid-frequency military sonar operate at relatively high speed and any marine mammal detections may occur too late to take useful action. Mitigation measures are also often based on insufficient data for species such as beaked whales which are thought to be very susceptible to the effects of sonar. More detailed research into the accumulative and synergistic effects of noise on marine mammal species is now being called for[595], which can contribute to the implementation of more consistent and stringent, science based mitigation policies.

There is clearly a lack of consistency in mitigation measures applied between the world's navies when planning for mitigating the damaging effects of sonar upon the marine environment. As a result there have been calls to move towards a science-based global standard of best practice for all nations' navies, offering adequate protection to all marine mammal species[596].

594 ACCOBAMS, 2007. Guidelines to address the impact of anthropogenic noise on marine mammals in the ACCOBAMS area. Resolution 3.10 Adopted at the Third Meeting of Parties.

595 Weilgart, L.S. 2007: The Impacts of anthropogenic ocean noise on cetaceans and implications for management.[http://www.nrcresearchpress.com/doi/abs/10.1139/Z07-101]

596 Dolman, S.J., Weir, C.R. and Jasny, M. (2009). Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin, 58: 465–477.

Table 4. Limitations of mitigation measures used for Active Sonar exercises and Seismic Surveys (adapted from Weir and Dolman 2007 and Dolman et al., 2009)

Mitigation Measure	Limitations for Active Sonar	Limitations for Seismic Surveys	Comments
Soft starts	Some sonar systems are not designed for soft start Existing guidance for operation is largely ambiguous for power levels (sound level and pulse duration)	Often the sole measure used at night and may not be effective for some species[597] Insufficient detail provided for the level of acoustic outputs for each stage of the soft start. No allowance for the variation in air-gun volume Often operated manually leading to variation in precision Independent monitoring of the procedure is challenging	Naval soft start guidance should provide specific information on the required increase in both sound level and pulse duration over time
Monitoring in adverse conditions	All current guidance depends on visual monitoring meaning there is effectively no mitigation in place for active sonar use occurring at night or in adverse weather conditions	No mitigation is effectively in place for operations at night Apart from reduced visibility, guidelines do not address adverse weather conditions	Visual monitoring at night is limited to 100 m with infra-red binoculars Visual detection of marine mammal species decreases significantly with increasing sea state[598]
Visual detection	Lack of appropriate training programmes and feedback processes for MMOs Lack of independence of MMOs	Lack of appropriate training programmes and feedback processes for MMOs Lack of independence of MMOs MMO reports not sent directly to the regulator Monitoring can be intermittent or absent if	Need for standardised training and assessment Clear potential for conflict of interests Independence of reporting process can be compromised

[597] McCauley RD et al. 1998. The Response of Humpback Whales (*Megaptera novaeangliae*) to Offshore Seismic Survey: Preliminary Results of Observations about a Working Seismic Vessel and Experimental Exposures.

[598] Clarke, R. 1982. An Index of Sighting Conditions for Surveys of Whales and Dolphins. Report of the International Whaling Commission 32

		MMOs are not on board	
Species included	Some regions currently offer no protection to dolphins and porpoises	No protection for dolphins and porpoises.	Small odontocetes are also affected by seismic surveys[599] or mid-frequency active sonar[600]
Exclusion zone	Scientific basis for defining exclusion zones is not clear	Scientific basis for defining exclusion zones is not clear	Exposure levels used to define zones[601] can be higher than scientifically recommended standards[602]
Pre-shoot watch	30 minute period used in most guidelines is not sufficient for deep water (>200m depth) May be ineffective for fast moving military vessels	30 minute period used in most guidelines is not sufficient for deep water (>200m depth)	Known dive times of some species (e.g., sperm whale and beaked whales) regularly equal or exceed 30 minutes. Naval vessels with active sonar can be travelling at high speeds e.g., 18 knots
Soft start delays	Most naval guidance does not require a soft start delay	Some guidelines do not define the length of the delay or when the soft start can re-commence	Only present in NATO naval guidance
Shut downs	Shut downs are not implemented for all marine mammals by some navies Procedure to follow a shut-down is unclear e.g., 30 minute clearance Most guidance does not stipulate a soft start after the shut-down.	Shut downs are not usually implemented for all marine mammals (e.g., small odontocetes) Can only be operated in daylight as require visual detection Procedure to follow a shut-down is unclear e.g., 30 minute clearance and/or soft start.	Consider specific shut down procedures for calves, which are more sensitive to anthropogenic sounds Animals may be in the locality of the source when full power resumes

[599] Goold. JC. 1996. Acoustic Assessment of Populations of Common Dolphin *Delphinus Delphis* in Conjunction with Seismic Surveying. J Mar Biol Assoc UK 76

[600] Rendell, L.E., Gordon, J.C.D., 1999. Vocal response of long-finned pilot whales (*Globicephala melas*) to military sonar in the Ligurian Sea. Marine Mammal Science 15, 198–204

[601] DOC. 2005. Draft Guidelines for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations. Department of Conservation, Wellington, New Zealand.

[602] Department of Fisheries and Oceans. 2005. Statement of Canadian Practice: Mitigation of Seismic Noise in the Marine Environment

PAM	Recognised but not being used to its full potential Lack of training and guidance on implementation	Not being used to its full potential Lack of training and guidance on implementation Often deployed more than 1 km ahead of the survey vessel	Prioritise the development of PAM training programmes PAM monitoring occurs too far from the air guns to be effective
Sensitive areas	Lack of rigorous definition of areas and how they apply to naval operations	Lack of rigorous definition of areas and how they apply to seismic operations	Only two countries[603] have defined prohibited areas for seismic surveys according to marine fauna Naval and seismic guidance should use clear criteria to define and implement mitigation measures in sensitive habitats, including time/area planning
Use of small volume air guns (as a mitigation method)	Not applicable	Variation in the duration of use e.g. for 24 hours or only at night Use is not restricted to the licensed prospecting area Concerns over time-sharing of firing between vessels in adjacent areas	No evidence that continual firing of a small gun acts as a deterrent to marine mammals. Some species may actively approach small volume air guns[604] Potential cumulative effects of continuous sound
Equipment operation		No overall restriction for air-gun use at night	Visual monitoring is limited to 100 m with infra-red binoculars
Other sources of disturbance	Guidance for minimising impacts to marine animals needs to address all activities during a naval exercise		Naval exercises often involve multiple vessels and activities which have the potential to disturb marine animals

[603] Barlow J and Gisiner R. 2006. Mitigating, Monitoring and Assessing the Effects of Anthropogenic Sound on Beaked Whales. Journal of Cetacean Research and Management 7
[604] McCauley RD et al. 1998. The Response of Humpback Whales (*Megaptera novaeangliae*) to Offshore Seismic Survey: Preliminary Results of Observations about a Working Seismic Vessel and Experimental Exposures

Noise profiles of other activities

Reducing the potential impacts of devices, such as Acoustic Harassment Devices (AHDs), on non-target species may be achieved through changing frequencies to those where non-target species are less sensitive, or by using responsive-mode devices that only emit sound when an animal approaches an area of interest. Similarly, it may be possible to use pingers that are triggered by echolocation activity of an approaching dolphin or porpoise. Changes in frequency of data transmission devices may help eliminate the potential risk to more sensitive species[605]. Noise levels of AHDs could be reduced by decreasing the duty cycle of the device. This will decrease the risk of hearing damage in target or non-target species and may reduce the likelihood of target species becoming habituated to the signal.

Decreasing the potential impacts of noise produced by marine renewable devices may be feasible at the design stage. It may not be possible to reduce noise levels through changes to individual turbines, but measures can be used to reduce the risk of "acoustic barrier effects" or specify the avoidance of important areas when designing the configuration of arrays of turbines, for example, to ensure that narrow channels used as transit routes for marine animals are not fully occluded by turbines, or critical habitats are not used to site arrays of turbines[606].

Reducing the effects of ocean tomography or thermometry studies, and data transmission devices, may be possible by ensuring that the immediate vicinity around the sound source is clear of animals through the use of exclusion zones using existing best practise guidelines or developing new specific guidance[607].

Playing temporarily aversive sounds that causes animals to show a small-scale avoidance response up to a certain distance from the sound source may provide a means of reducing physical injury such as hearing damage. This may be feasible for temporary noise activities like ocean tomography studies or acoustic data transmission. With all species, planning activities so that their timing will reduce the likelihood of encounters with breeding areas or juvenile animals, using the lowest practicable power levels throughout the survey, and seeking methods to reduce and/or baffle unnecessary frequencies from the devices will lead to reduced risk of injury, masking, and behavioural responses.

The use of marine protected areas to restrict or reduce the effects of anthropogenic noise can also be applied to all the aforementioned sound sources. This particularly needs to be considered for the increasing use of the coastal and inshore zone by small and medium-sized vessels.

No information is available for the mitigation of the environmental effects of any non-military sonars operated by small to medium-sized vessels. In fact there seem to be no published studies on how commercial sonars, depth finders and fisheries acoustics gear may influence the distribution and behaviour of cetaceans[608] or other marine animals.

Management frameworks and expert processes

Working groups have been set up by a number of bodies recently, to address the issues surrounding marine noise and its negative effects on marine fauna. Many of these groups have established expert committees, in an effort to improve mitigation and legislation, or developed detailed management framework concepts.

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[605] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission. 133 p.

[606] Ibid

[607] Ibid

[608] Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. Mammal Review, 37: 81 – 115

In 2004, the National Oceanic and Atmospheric Administration (NOAA) hosted an initial meeting, entitled "Shipping Noise and Marine Mammals: A Forum for Science, Management and Technology", which essentially served as an introduction of this issue to industry representatives, conservation managers and scientists from various fields[609]. At that meeting, a number of recommendations for future action and consideration were made, including the need for a greater scientific basis for assessing the relative magnitude of the potential problem and various mitigation measures directed to reduce impacts. The following publication was produced[610], whereby the following future recommendations were decided upon:

- Compile a "menu" of existing quieting technologies (retrofitting & new construction), their likely feasibility in terms of meeting specified goals for noise reduction of large vessels, and anticipated costs/ benefits in specified categories. Identify potential technologies unlikely to succeed for large vessels.
- Discuss conclusions and caveats for the most promising technical approaches, with consideration of which ships have the greatest sound output, which classes are most numerous generally and in areas that are most significant biologically.
- Discuss costs/benefits for marine mammals and their management from vessel-quieting, specifically the potential interactions between vessel-quieting and marine mammal ship-strike issues
- Identify and plan the next steps regarding large vessel sounds and marine life.

Recently, the European Commission Joint Research Centre under the Marine Strategy Framework developed a task group charged with investigating the effects of underwater noise and other forms of energy[611]. The report outlines the limited extent of knowledge of the effects of underwater energy, particularly noise, and particularly at any scale greater than the individual/group level. The report contains much background scientific information and has suggestions for possible further indicators in the future for noise, as well as on the assessment of the effects of electromagnetic fields and heat on the marine environment.

Excluding anthropogenic marine noise from certain zones is considered to be one of the most effective mitigation strategies[612]. A Workshop on the Spatio-Temporal Management of Noise was undertaken in 2007 in Spain[613]. Workshop participants agreed that there is a need to develop a systematic protocol for identifying and prioritising noise mitigation actions. A six-step Framework was the main outcome from the meeting, which draws upon some of the general principles of conservation planning and adaptive management, whilst also being tailored to the context of noise mitigation for cetaceans. The six steps are:

- Define the goal(s), constraints and geographic scope of the planning process;

[609] Southall, B. L. 2005. Final report of the NOAA International Symposium: "Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology," 18-19 May, 2004, Arlington, VA, U.S.A.

[610] Final Report of the National Oceanic and Atmospheric Administration (NOAA) International Symposium: Potential Application of Vessel-Quieting Technology on Large Commercial Vessels 1-2 May, 2007 Silver Spring, Maryland, U.S.A.

[611] M.L. Tasker, M. Amundin, M. Andre, A. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilmann, F. Thomsen, S. Werner & M. Zakharia. Marine Strategy Framework Directive. Task Group 11. Report Underwater noise and other forms of energy.

[612] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission.

[613] Agardy, T., Aguilar, N., Cañadas, A., Engel, M., Frantzis, A., Hatch, L., Hoyt, E., Kaschner, K., LaBrecque, E., Martin, V., Notarbartolo di Sciara, G., Pavan, G., Servidio, A., Smith, B., Wang, J., Weilgart, L., Wintle, B. and Wright, A. 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise. Report of the Scientific Workshop. 44 pages. http://www.okeanos-foundation.org/assets/Uploads/str2007en2.pdf

- Identify relevant data and data gaps;
- Synthesise habitat and threat data to generate exposure ranking maps;
- Generate map of mitigation priority areas;
- Identify and prioritise actions for priority conservation zones, and;
- Implement and monitor.

A draft research strategy was developed based on the activities and proceedings of an Expert Group on anthropogenic sound and marine mammals convened at the joint Marine Board- ESF and National Science Foundation (US) Workshop on October 4-8 2005[614]. The outcomes of this work put forward recommendations for a four-step analytical risk framework process adapted to the issue of marine mammals and anthropogenic sound to assess and identify priority research topics for reducing uncertainty. The risk framework process includes hazard identification, characterizing exposure to the hazard, characterizing dose-response relationships and risk characterization, typically feeding into a risk management step (Box 1). A rationale was developed to help prioritise research questions and to develop a set of approaches that could be used to help answer these questions[615]. The risk framework process could also be applied to other marine fauna such as marine turtles, fish and invertebrates.

A four-step analytic process is applied. A sound leaves a source (e.g., sonar transducer, seismic airgun array), moves through the water, and results in an exposure (marine mammals receiving sound). The exposure creates a dose in the exposed animals (the type and amount of the sound received by the animals, which may be expressed in any of several ways), and the magnitude, duration, timing, and other characteristics of the dose determine the extent to which there is an effect. This model is captured in the following analytic steps:

Step 1:

Hazard Identification: entails identification of the sound sources and the circumstances in which they are used that are suspected to pose hazards, quantification of the concentrations at which they are present in the environment, a description of the specific effects of the sound source, and an evaluation of the conditions under which these effects might be expressed in exposed marine mammals. Information for this step may be derived from environmental monitoring data and the direct correlation of effect with the presence of a hazard as well as other types of experimental work. This step is common to qualitative and quantitative risk assessment.

Step 2:

Dose-Response Assessment: entails a further evaluation of the conditions under which the effects of sound might be manifest in exposed marine mammals, with particular emphasis on the quantitative relation between the dose and the response. This step may include an assessment of variations in response, for example, differences in susceptibility in relation to age, sex, reproductive status and time of year.

Step 3:

Exposure Assessment: involves specifying the population that might be exposed to the hazard, identifying the routes through which exposure can occur, and estimating the characteristics (magnitude, duration, and timing) of the doses that marine mammals might receive as a result of their exposure.

Step 4:

Risk Characterization: involves integration of information from the first three steps to develop a qualitative or quantitative estimate of the likelihood that any of the hazards associated with the sound source will be realized in exposed marine mammals. This is the step in which risk-assessment results are expressed. Risk characterization should also include a full discussion of the uncertainties associated with the estimates of risk.

Box 1. The Risk Assessment Framework (after Boyd et al., 2008)

[614] Boyd, I., 2008. The effects of anthropogenic sound on marine mammals. A draft research strategy. Report Produced from the Joint Marine Board-ESF and National Science Foundation (US) Workshop at Tubney House on October 4–8, 2005.
[615] Ibid – Tables 3 and 4 for beaked whale research questions

Both the Agreement on the Conservation of Cetaceans in the Black Sea Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS)[616] and the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) [617] have established working groups that address underwater noise and have produced guidelines for its mitigation. These two groups are now working on producing joint summaries of these guidelines for specific stakeholders, e.g. relating to renewable energy, military, seismic surveys and shipping.

The 2009 European Cetacean Society (ECS) Conference included a workshop addressing the issue of 'Beaked whales and active sonar: Transiting from research to mitigation'. A small working group of relevant experts was set up to produce a technical report[618]. This report discusses practical effective techniques to apply mitigation in order to reduce impact of active sonar on cetaceans. The working group concluded that standards should be developed that define an appropriate level of cetacean monitoring, depending on the species. To improve the effectiveness of real-time mitigation, such measures must reflect the challenges involved in detecting some of the most sonar sensitive species. The working group recommended that navies adopt the following measures for real-time mitigation:

Effective detection of cetaceans present in the exercise area

- Monitoring with an appropriately designed array of visual and passive acoustic sensors in the exercise area during operation. Where available, on-range hydrophone networks should be utilised for real-time mitigation: otherwise, temporary hydrophone arrays of adequate size and sensitivity to reliably detect beaked whales should be used;
- Acoustic monitoring using transparent protocols for detection and classification of cetacean vocalisations. For beaked whales, on-range hydrophone networks and networks of temporary hydrophone arrays are potentially useful methods upon which efforts should continue to be focused;[619]
- Pre-sonar watch of a predetermined period (at least 2 hours for beaked whale detection) in which to provide the best chance to detect all available cetaceans visually (on board and where possible from aerial surveys) and acoustically;
- Use of dedicated, experienced and, where possible, independent marine mammal observers, trained to a minimum standard on visual and acoustic detection of beaked whales; and
- Assuming visual monitoring is maintained for the protection of other species, restriction of operation, to the greatest extent possible, to observable visual conditions, such as during good light (during the daytime) and appropriate environmental conditions (including a sea state <3).

Mitigation requirements once cetaceans are detected:

- Sonar power reduction and shut-down within conservatively defined radii to the greatest extent practicable around the sonar array, based on models of sound transmission (verified in local conditions) and of effects of sonar on sensitive species. For beaked whales (and likely for other species and situations), a conservatively defined radius would extend to the isopleth where the

[616] ACCOBAMS 2010: Fourth Meeting of the Parties, Res. 4.17 "Guidelines to address the impact of anthropogenic noise on cetaceans in the ACCOBAMS area"

[617] ASCOBANS AC17/Doc.4-08 (WG) Final Report of the ASCOBANS Intersessional Working Group on the Assessment of Acoustic Disturbance

[618] ASCOBANS **AC16/Doc.50 (O)** Technical Report on Effective Mitigation for Active Sonar and Beaked Whales, Dist. 26 March 2009

[619] André, M., van der Schaar, M., Zaugg, S., Mas, A., Morell, M., Solé, M., Castell, J.V. and Sánchez, A. 2009. Real-time detection of beaked whale sonar signals over background noise and other acoustic events. Challenges of sonar mitigation for beaked whales. Presentation at the Workshop on Beaked whales and active sonar: transiting from research to mitigation. 23rd Conference of the European Cetacean Society held in Istanbul, Turkey.

risk of significant behavioural effects becomes more than negligible (acknowledging that this might be beyond the radius of visibility);

- Suspension or relocation of activities where detections of potentially affected species are higher than predicted in pre-exercise planning. Suspension, relocation, or other restrictions are also warranted where detections of potentially affected species are higher than predicted in pre-exercise planning, or where unexpected oceanographic conditions such as surface-ducting would result in higher numbers of impacts than predicted.

V. FUTURE RESEARCH NEEDS

This assessment of anthropogenic noise and its impact on marine organisms has highlighted the extent of knowledge gaps and uncertainties for this issue. The current status of scientific knowledge (in terms of the level and types of sound that will result in a specific effect) often results in estimates of potential adverse impacts that contain a high degree of uncertainty[620]. These uncertainties need to be addressed in a systematic manner to fully understand the effects of increased noise from human activities in the marine environment. There are a suite of future research needs that have to be addressed to both better characterise and quantify anthropogenic noise in the marine environment and the impact it has on marine organisms. However, the extensive knowledge gaps also mean that prioritisation will be required. Detailed research programmes of noise effects on species, populations, habitats and ecosystems as well as cumulative effects with other stressors need to be put in place or consolidated where they already exist. Current knowledge for some faunal groups such as elasmobranch fish, marine turtles, seabirds and invertebrates is particularly lacking. Other priorities for acoustic research are endangered or threatened marine species and critical habitats they depend upon for important activities such as foraging or spawning. Marine species that support commercial fisheries should also be assessed for susceptibility to noise pollution and the issue of anthropogenic noise considered for fisheries management plans. Existing or proposed management frameworks also need to be tested and refined accordingly in a range of scenarios. A number of current or proposed large-scale research programmes are addressing a range of issues with a focus on marine mammals. However, there is a need to scale up the level of research and management efforts to significantly improve our understanding of the issue and minimise our noise impacts on marine biodiversity.

There have been a number of reviews of research needs in recent years that have mainly focussed on marine mammals[621] [622] [623] and also specific research needs for other taxa[624] [625] in the literature. The main research priorities recommended by these reviews are summarised in Table 5. Details of these recommendations will be incorporated into the following sections as appropriate.

Research needs can be split into four main areas:

- Further characterisation of underwater noise and properties of emitted sound in a changing marine environment
- Baseline data on the biology, distribution, abundance and behaviour of marine species
- Detailed information on the impacts of sound on marine animals at the individual, population and ecosystem level
- Assessment and improvement of mitigation procedures and measures

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620 Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

621 MMC (Marine Mammal Commission) 2007. Marine mammals and noise: a sound approach to research and management. Marine Mammal Commission, Bethesda, Maryland. 370pp.

622 Boyd, I., 2008. The effects of anthropogenic sound on marine mammals. A draft research strategy. Report Produced from the Joint Marine Board-ESF and National Science Foundation (US) Workshop at Tubney House on October 4–8, 2005.

623 Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

624 Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

625 Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243

ANTHROPOGENIC SOURCES AND AMBIENT NOISE

Although there has been considerable previous investment in the collection of underwater sound data for commercial, military or research purposes our knowledge of anthropogenic sound fields in the marine environment is incomplete[626]. The seas and oceans are also becoming noisier as marine-based human activities increase in diversity and intensity, particularly in coastal and shelf waters (Figure 7). Ambient noise levels for mid and high frequencies are increasing with the greater use of sonar and increased small boat traffic[627]. Anthropogenic noise sources are also often distributed heterogeneously in time and space which contributes to the complexity of underwater 'soundscapes' that marine organisms inhabit[628]. In addition, the different components of anthropogenic sound attenuate at different rates depending on their frequency and environmental conditions further increasing complexity and making it difficult to predict the actual sound levels received by marine organisms[629]. The type of sound is also important in terms of whether it is a continuous emission over a long time period or a series of short intermittent pulses causing different chronic or acute effects even though the power of the sound emitted is the same.

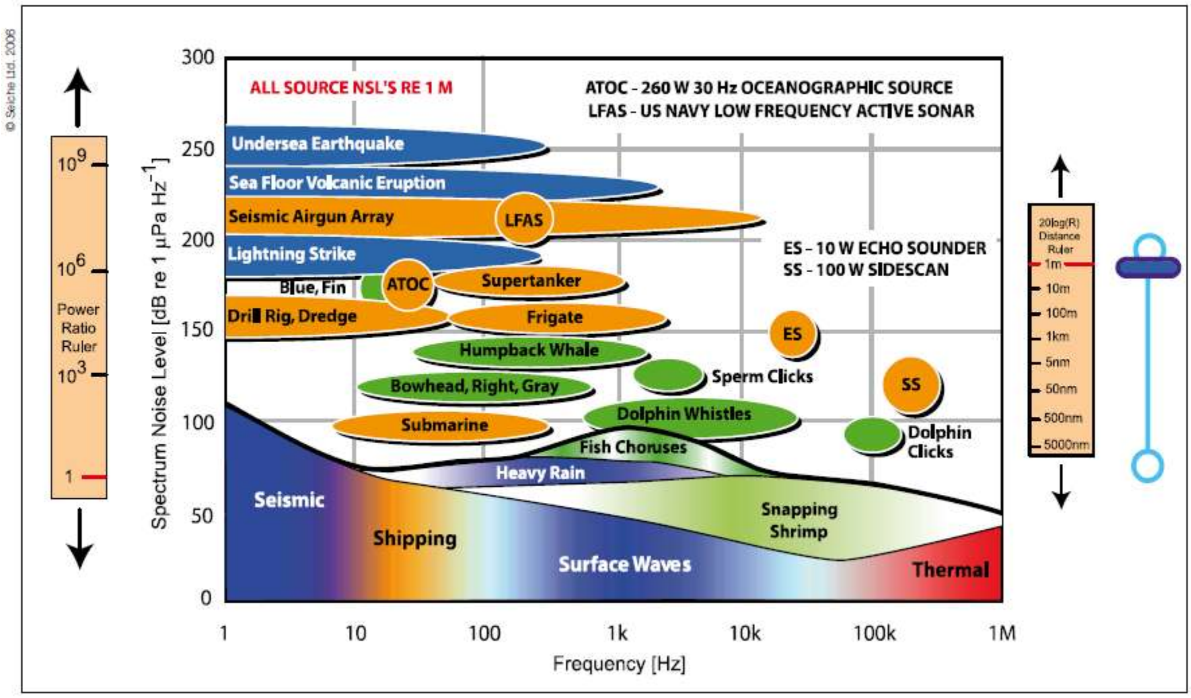

Figure 7. Noise levels and frequencies of anthropogenic and naturally occurring sound sources in the marine environment (Seiche graphic)

Further quantification of the underwater acoustic environment is therefore required. Increased levels of passive (or active) acoustic monitoring are needed to detect and characterise both biological and anthropogenic sound sources and collect ambient noise information for key areas. Anthropogenic sources considered to be of the highest concern (in the United States) are certain military sonars, ice-breaking, seismic air guns and new classes of large vessels closely followed by wide-azimuth seismic

[626] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[627] Ibid

[628] Boyd, I., 2008. The effects of anthropogenic sound on marine mammals. A draft research strategy. Report Produced from the Joint Marine Board-ESF and National Science Foundation (US) Workshop at Tubney House on October 4–8, 2005

[629] Ibid

surveys, pile driving, as well as oil drilling and production[630]. Priorities for action are likely to change somewhat at the national level depending on the key activities and sound sources present or planned within areas under national jurisdiction. Regional or ocean-wide priorities for acoustic research will need to be considered and agreed through regional or global bodies.

Passive acoustic monitoring can also provide real-time information to characterise ambient sound fields and feed into models to predict future trends. To model ambient noise levels a better understanding of the signal characteristics of anthropogenic sources is needed[631]. For example further information for the key parameters that make up the noise spectra of ships and also smaller vessels is required. With improved source profiles and an understanding of how the level of activity exactly contributes to the resulting ambient noise profile, researchers can extend noise modelling so that better predictions can be made for regions with known anthropogenic activities but are currently lacking in acoustic information[632].

More detailed information on the location and distribution of anthropogenic noise sources in the oceans can contribute to real-time estimations of regional or global noise levels as part of large-scale ocean monitoring systems. For example the geographic position of commercial vessels or the tracklines for seismic profiling could be used in models along with data on environmental variables (bathymetry, sound speed profiles, wind and wave noise spectra) to provide a more accurate assessment of the relative contribution of natural and anthropogenic noise sources[633].

There is also a need for further research to predict the effects on declining ocean pH on the properties of underwater sound. As ocean acidity increases there is a corresponding reduction in the absorption of low frequency sound (100 Hz - 10 kHz)[634] [635] and the mechanism for this chemical relaxation-based acoustic energy loss is well known[636]. More than 50% reduction in the absorption of sound at 200 Hz has been predicted in high latitudes (e.g., North Atlantic) by 2100[637] although these predictions have recently been disputed by subsequent modelling studies[638]. If the former predictions are the more likely scenario then there is the potential that marine organisms sensitive to low frequency sound (e.g., baleen whales) will be more susceptible, particularly in acoustic hotspots where high levels of anthropogenic noise (e.g., shipping) coincide with the greatest drop in absorption.

BASELINE BIOLOGICAL INFORMATION

To understand how anthropogenic noise is having an impact on marine biodiversity it is important that we also know as much as possible about a particular species both in terms of its biology and ecology. Information for species and populations is incomplete for many marine animals, particularly for

[630] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

[631] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20

[632] Ibid.

[633] Ibid

[634] Hester, K.C., Peltzer, E.D., Kirkwood, W.J. and Brewer, P.G. 2008. Unanticipated consequences of ocean acidification: a noisier ocean at lower pH. Geophysical Research Letters. 35. doi:10.1029/2008GL034913

[635] Ilyina, T., Zeebe, R.E. and Brewer, P.G. 2009. Future ocean increasingly transparent to low-frequency sound owing to carbon dioxide emissions. Nature Geoscience Vol 3: 18-22

[636] Francois, R. E., and Garrison, G. R. (1982). "Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption," J. Acoust. Soc. Am. 72, 1879–1890.

[637] Ilyina, T., Zeebe, R.E. and Brewer, P.G. 2009. Future ocean increasingly transparent to low-frequency sound owing to carbon dioxide emissions. Nature Geoscience Vol 3: 18-22

[638] Udovydchenkov, I.A., Duda, T.F., Doney, S.C. and Lima, I.D. 2010. Modeling deep ocean shipping noise in varying acidity conditions. J. Acoust. Soc. Am. 128. DOI: 10.1121/1.3402284

invertebrates but also for many marine fish and mammals (e.g., beaked whales). The scale of this task suggests that a system of prioritisation is needed. Marine species that are known or highly likely to be susceptible to the effects of anthropogenic noise but are also threatened by other stressors such as overexploitation, habitat loss or other forms of pollution are one of the highest priorities. In addition many threatened species will be lacking in basic biological information that is relevant to underwater acoustics. For example elasmobranch fish are recognised as highly threatened taxa[639] but very little is known about their sense of hearing with data available for only a few species[640]. Research is therefore required for species that are data deficient in terms of auditory biology, hearing sensitivity and how they use sound for communication or for key life processes such as feeding or predator avoidance. Again, due to the number of species involved, research could focus on representative[641] species as surrogates for less-common or more-difficult-to-test species[642] or on a wide range of morphologically and taxonomically diverse species of interest[643]. Representative species could be selected according to trophic group, lifestyle (e.g., pelagic or demersal/benthic) or life history stage. In addition to an improved understanding of the importance of sound to marine organisms it is equally important to collect detailed information on the distribution, behaviour and population size of selected species. Knowing what constitutes normal behaviour and which habitats are preferred by marine species at particular times will enable more effective management and mitigation measures to be made.

Another priority is the use of all reliable biological information currently available for species from a range of sources (e.g., fisheries data for stocks and distribution, marine mammal monitoring data, tagging studies for marine turtles, teleost fish or elasmobranchs) to help build up a more coherent picture of the life history traits for that organism. The development and maintenance of standardised online databases has been highly prioritised for marine mammals[644] and could be applied to other groups of marine vertebrates such as teleost and elasmobranch fish and marine turtles.

NOISE IMPACTS ON MARINE BIODIVERSITY

The high level of uncertainty for many species also applies to our current knowledge of the impacts of anthropogenic noise. It will therefore be necessary to prioritise which marine species are selected for research and the same criteria mentioned previously for selection should apply. High priority research areas are listed in Table 6 and include anthropogenic noise effects on individuals in terms of physical damage, physiology and behaviour but also the long-term effects on populations and the cumulative effects of noise in combination with other stressors. There is considerably more known about the effects of anthropogenic noise on marine mammals than other taxa. One further prioritisation criterion could be to markedly increase the knowledge base for data-deficient groups (e.g., marine fish, turtles and invertebrates).

An overarching priority is to increase the collection of field-based data for behavioural (and other) long-term responses of individuals to anthropogenic sound rather than relying on data collected in

[639] Godin AC, Worm B (2010) Keeping the lead: How to strengthen shark conservation and management policies in Canada. Mar Policy 34:995-1001

[640] Casper, B.M., Halvorsen, M.B. and Popper, A.N. (in press). Are sharks even bothered by a noisy environment?

[641] those thought to adequately represent related species on which such data are not available

[642] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

[643] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

[644] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

laboratory or enclosed conditions. This is particularly required for teleost fish where it is not possible to extrapolate from studies of caged fish to wild animals[645] and only a few studies have observed noise impacts on free-living fish in their natural environment[646]. For non-behavioural research new technology may need to be developed to monitor particular noise effects *'in situ'* via 'smart' tags e.g., for measurements of hearing loss, metabolism and the production of stress hormones.

The more long-term chronic and also cumulative effects of anthropogenic noise on marine organisms and populations have received some attention in recent years, particularly for marine mammals[647] [648], but are in need of thorough assessment for other taxa as well (e.g., teleost and elasmobranch fish, marine turtles and invertebrates). It is known that chronic disturbance in the coastal environment can lead to reduced reproductive success in some cases[649] and further research studies are required to investigate whether this is also the case for other marine fauna. Reproductive success may also be compromised by changes in behaviour (e.g., avoidance of spawning sites) or masking of communication between potential mates[650].

Increasing levels of ambient noise in marine and coastal environments have led to concerns of masking of important biological signals either received or emitted by marine organisms. Although this has theoretically been demonstrated for marine mammals[651], there is little evidence to confirm masking in other marine taxa. Teleost fish are one group where acoustic reception and communication can be highly important for survival or reproduction[652]. Masking of important orientation cues may also occur for both fish and invertebrate larvae prior to settlement[653] [654]. The potential for masking in a range of marine taxa is apparent and the risk of an impact is likely to increase as anthropogenic noise levels rise in shallow seas. This should be regarded as a high priority research need as it has the potential to affect multiple species simultaneously with long-term consequences for populations and communities.

The socio-economic consequences of noise-induced impacts on marine populations have not been considered by the research community. Avoidance of noisy areas or reduced population success may

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[645] Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

[646] Wardle, C. S., Carter, T. J., Urquhart, G. G., Johnstone, A. D. F., Ziolkowski, A. M., Hampson, G. & Mackie, D. (2001). Effects of seismic air guns on marine fish. Continental Shelf Research 21, 1005–1027.

[647] Wright, A.J., Soto, N.A., Baldwin, A.L., Bateson, M., Beale, C.M., Clark, C., Deak, T., Edwards, E.F., Fernández. A., Godinho, A., Hatch, L.T., Kakuschke, A., Lusseau, D., Martineau, D., Weilgart, L.S., Wintle, B.A., Notarbartolo-di-Sciara, G. and Martin, V. 2007. Do marine mammals experience stress related to anthropogenic noise? International Journal of Comparative Psychology, 20: 274 – 316.

[648] Wright, A.J. (ed) 2009. Report of the Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action. Monterey, California, USA, 26th-29th August, 2009. Okeanos - Foundation for the Sea, Auf der Marienhöhe 15, D-64297 Darmstadt. 67+iv p. http://www.okeanos-foundation.org/assets/Uploads/CIReportFinal3.pdf

[649] Bejder L (2005) Linking short and long-term effects of nature-based tourism on cetaceans. PhD dissertation, Dalhousie University, Halifax, NS

[650] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243

[651] Clark, C.W., Ellison, W.T., Southall, B.L., Hatch L., van Parijs, S.M., Frankel, A. and Ponirakis, D. 2009. Acoustic masking in marine ecosystems: intuitions, analyses, and implication. Marine Ecology Progress Series, 395: 201 – 222

[652] Slabbekorn, H., Bouton, N., van Opzeeland, I., Coers, A, ten Cate, C and Popper, A.N. 2010. A noisy spring: the impact of globally rising underwater sound levels on fishes. Trends in Ecology and Evolution 1243

[653] Simpson SD, Meekan MG, Jeffs A, Montgomery JC, McCauley RD. 2008. Settlement-stage coral reef fishes prefer the higher frequency invertebrate-generated audible component of reef noise. Anim Behav 75:1861–8.

[654] Simpson SD, Radford AN, Tickle EJ, Meekan MG, Jeffs AG (2011) Adaptive Avoidance of Reef Noise. PLoS ONE 6(2): e16625. doi:10.1371/ journal.pone.0016625

have a significant effect on catches of commercial fish or invertebrate species. Seismic surveys have previously been linked to short-term reductions in catch levels[655].

Reviews have also highlighted methodological issues in experimental design and the need for proper controls and pathology (where applicable) as well as careful measurement of sound sources and signals and the use of proper sound metrics[656] [657] [658]. Standardisation in research studies will help to both define the sound field received but also allow for comparisons of source signals of different types[659].

MITIGATION AND MANAGEMENT

The mitigation and management of anthropogenic noise in the marine environment has been extensively covered in the previous chapter. This highlighted a number of issues that currently exist with commercial and government approved mitigation procedures for marine activities emitting underwater noise. There is a need to critically assess the effectiveness of such mitigation procedures[660] through an independent peer-reviewed process. Measuring the efficacy of mitigation measures such as 'soft start' in naval sonar exercises is also required. Once existing mitigation procedures and measures have been assessed, recommendations and guidelines can then be provided to the relevant practitioners. The long-term aim is the production of global standards that nations (and their military, for sonar operations) can sign up to and considerable progress has been made to achieve this for marine mammals[661] [662].

As well as improving mitigation procedures and measures it is important that industry is encouraged to improve existing mitigation tools such as the mechanisms of sound emission by developing quieter noise sources through engineering modifications (e.g., shorter duration, narrower directionality or eliminating unnecessary frequencies)[663] [664] [665]. The development of passive acoustic monitoring (PAM) systems or other remote sensing techniques to detect a range of marine taxa is an important

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655 Engås, A. & Løkkeborg, S. (2002). Effects of seismic shooting and vessel-generated noise on fish behaviour and catch rates. Bioacoustics 12, 313–315.

656 Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

657 Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

658 Moriyasu et al., 2004. Effects of seismic and marine noise on invertebrates: A literature review. Canadian Science Advisory Secretariat. Research document 2004/126

659 Popper, A.N. and Hastings, M.C. 2009a. The effects of anthropogenic sources of sound on fish. Journal of Fish Biology, 75: 455 – 489.

660 Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477

661 Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27.

662 Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477

663 Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85: 1091-1116

664 Weilgart, L.S. (ed) 2010. Report of the Workshop on Alternative Technologies to Seismic Airgun Surveys for Oil and Gas Exploration and their Potential for Reducing Impacts on Marine Mammals. Monterey, California, USA, 31st August – 1st September, 2009. Okeanos - Foundation for the Sea, Auf der Marienhöhe 15, D-64297 Darmstadt. 29+iii pp. http://www.okeanos-foundation.org/assets/Uploads/Airgun.pdf

665 Weilgart, L. 2012. Are there technological alternatives to air guns for oil and gas exploration to reduce potential noise impacts on cetaceans? In: Popper, A.N., and A. Hawkins (Eds.). The Effects of Noise on Aquatic Life, Advances in Experimental Medicine and Biology 730: 605-607, New York: Springer Press.

step for improving mitigation[666]. For example, PAM will become more successful as a mitigation tool if it is able to accurately detect a significant number of vocalising marine mammal species within exclusion zones, identify each marine mammal species and provide a reliable range measurement to the animal[667].

Current research programmes such as the International Quiet Ocean Experiment (IQOE)[668] and the Listening to the Deep Ocean (LIDO) project[669] are important elements in improving our understanding of underwater sound and anthropogenic noise in our oceans and need to be supported over the long-term.

[666] Southall, B., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W., Lewandoski, J., Wilson, J., and Winokur, R. 2009. Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. federal agencies. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology. Washington, DC

[667] Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27.

[668] Boyd, I.L., G. Frisk, E. Urban, P. Tyack, J. Ausubel, S. Seeyave, D. Cato, B. Southall, M. Weise, R. Andrew, T. Akamatsu, R. Dekeling, C. Erbe, D. Farmer, R. Gentry, T. Gross, A. Hawkins, F. Li, K. Metcalf, J.H. Miller, D. Moretti, C. Rodrigo, and T. Shinke. 2011. An International Quiet Ocean Experiment. *Oceanography* 24(2):174–181

[669] Andre, M., van der Schaar, M., Zaugg, S., Houegnigan, L., Sanchez, A.M. and Castell, J.V. 2011. Listening to the Deep: live monitoring of ocean noise and cetacean acoustic signals. Mar Poll Bull 63:18-26.

Table 5. Priority research needs for Anthropogenic Noise and its impact on Marine Biodiversity (adapted from Boyd et al., 2008; Southall et al., 2009; Tasker et al., 2010)

Subject Area (s)	Research Priorities	Biodiversity Conservation Priorities
Marine acoustics and monitoring	Long term biological and ambient noise measurements in high-priority areas (*e.g.*, protected areas, critical habitats, commerce hubs,) and more widely at the ocean basin level to record trends	Migratory corridors; foraging, mating / spawning and nursery habitats Identification of remaining quiet areas and ambient noise hotspots
	Determine the characteristics, distribution and abundance of anthropogenic sound sources in the marine environment	Identify 'noisy hotspots' where multiple sources occur
	Develop new technologies (*e.g.*, acoustic monitoring) to detect, identify, locate, and track marine vertebrates, in order to increase the effectiveness of detection and mitigation.	Monitoring of susceptible groups (e.g., beaked whales) and non-vocal vertebrates (e.g., teleost fish, elasmobranchs, turtles)
Baseline Biological Information	Biological research on: • Acoustic sensory organs structure and function • Use of sound by marine organisms; • Species-specific communication maximum ranges; • Basic information on hearing, especially for low frequency and high frequency species; • Modelling of the auditory system (to reduce dose response experimental exposure to sound).	Data deficient taxa: Teleost fish, Elasmobranchs, Marine Turtles, Invertebrates Marine species that are endangered and/or highly susceptible to multiple stressors
	Expand/improve distribution, abundance, behavioural and habitat data for marine species particularly susceptible to anthropogenic sound	Beaked whales, Threatened cetaceans
	Expand/improve distribution, abundance, behavioural and habitat data for marine species	Teleost fish, invertebrates

	with high potential susceptibility to anthropogenic sound	(Cephalopods)
Baseline Biological Information and Monitoring	Support the development, standardization, and integration of online data archives of marine vertebrate distribution, abundance, and movement for use in assessing potential risk to marine vertebrates from sound-producing activities.	
	Standardize data-collection, reporting, and archive requirements of marine vertebrate monitoring programmes	Marine mammals, Marine turtles, Selected fish (apex predators, threatened keystone species), selected invertebrates
Sound effects on marine organisms	Data collection, involving controlled exposure experiments, for key species of concern and/or for data deficient taxa for sound effects (where applicable) on: • Hearing loss (TTS/PTS) and auditory damage (e.g., sensory hair cells) • Physiological (e.g., stress effects); • Behavioural – e.g., avoidance / displacement or disruption of normal activity; • Non-auditory injury – barotrauma, embolism, DCS • Masking – communication and orientation • Particle motion impacts	Key concerns: baleen whales, beaked whales, Arctic & endangered species of marine mammal) Data deficient taxa: Teleost fish, Elasmobranchs, Marine Turtles, Invertebrates
	Investigate cumulative effects of noise and stressors on marine organisms for both: • multiple exposures to sound • sound in combination with other stressors	Identify noise exposure criteria for cumulative effects
	Improve ability to identify and understand biologically-significant effects of sound exposure in order to improve effectiveness and efficiency of efforts to mitigate risk	
Sound effects on marine populations and communities	Measure changes in vital rates, e.g., fecundity, survival for populations. Measure changes in community composition.	Endangered species with small populations and limited distribution or mobility

Mitigation	Develop and improve noise exposure criteria and policy guidelines based on periodic reviews of best available science to better predict and regulate potential impacts	
	Develop and validate mitigation measures to minimize demonstrated adverse effects from anthropogenic noise	
	Test/validate mitigating technologies to minimize sound output and/or explore alternatives to sound sources with adverse effects (*e.g.*, alternative sonar waveforms).	

VI. CONCLUSIONS

The levels of anthropogenic noise in the marine environment have increased substantially in the last century[670] as human activities in coastal and oceanic waters have expanded and diversified. The underwater world is subject to a wide array of man-made noise from activities such as commercial shipping, oil and gas exploration and the use of various types of sonar[671]. The level of activity is also predicted to rise over the coming decades as maritime transportation and the exploration and extraction of marine resources continues to grow[672].

Sound is extremely important to many marine animals and plays a key role in communication, navigation, orientation, feeding and the detection of predators[673]. From invertebrate larvae[674] to the largest animals on the planet[675], the detection and recognition of underwater sound is crucial. The use of sound underwater is particularly important to many marine mammals such as cetaceans and especially the toothed whales which have highly specialised echolocation abilities. Many other marine taxa also rely on sound on a regular basis including teleost fish and invertebrates such as decapod crustaceans. The importance of sound for many marine taxa is still rather poorly understood and in need of considerable further investigation.

Concerns about the impacts of anthropogenic sound on marine animals have grown steadily over the last four decades. The levels of introduced noise in the marine environment are now considered to be a global issue and a significant stressor for marine life. Noise is listed as one of the impacts that can result in a substantial loss of biodiversity over time in sensitive marine habitats[676].

A wide range of effects of increased levels of sound on marine fauna have been documented both in laboratory and field conditions. Low levels of sound can be inconsequential for many animals. However, as sound levels increase the elevated background noise can disrupt normal behaviour patterns leading to less efficient feeding for example. Masking of important acoustic signals or cues can reduce communication between conspecifics[677] and may interfere with larval orientation which could have implications for recruitment. Some marine mammals have tried to compensate for the elevated background noise levels by making changes in their vocalisations[678].

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[670] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp

[671] Hildebrand, J. A. 2005. Impacts of anthropogenic sound. – in: Reynolds, J.E. et al. (eds.), Marine mammal research: conservation beyond crisis. The Johns Hopkins University Press, Baltimore, Maryland, pp 101-124

[672] Boyd, I.L., G. Frisk, E. Urban, P. Tyack, J. Ausubel, S. Seeyave, D. Cato, B. Southall, M. Weise, R. Andrew, T. Akamatsu, R. Dekeling, C. Erbe, D. Farmer, R. Gentry, T. Gross, A. Hawkins, F. Li, K. Metcalf, J.H. Miller, D. Moretti, C. Rodrigo, and T. Shinke. 2011. An International Quiet Ocean Experiment. *Oceanography* 24(2):174–181

[673] Richardson, W.J., Malme, C.I., Green, C.R.jr. and D.H. Thomson (1995). Marine Mammals and Noise. Academic Press, San Diego, CA 576 pp

[674] Vermeij MJA, Marhaver KL, Huijbers CM, Nagelkerken I, Simpson SD (2010) Coral Larvae Move toward Reef Sounds. PLoS ONE 5(5): e10660. doi:10.1371/ journal.pone.0010660

[675] Stafford, K. M., C. G. Fox, and D. S. Clark. 1998. Long-range acoustic detection and localization of blue whale calls in the northeast Pacific. Journal of the Acoustical Society of America 104:3616–3625

[676] Warner, R. 2008.Protecting the diversity of the depths: environmental regulation of bioprospecting and marine scientific research beyond national jurisdiction. Ocean Yearbook. 22: 411-443.

[677] Clark, C.W., Ellison, W.T., Southall, B.L., Hatch L., van Parijs, S.M., Frankel, A. and Ponirakis, D. 2009. Acoustic masking in marine ecosystems: intuitions, analyses, and implication. Marine Ecology Progress Series, 395: 201 – 222

[678] Holt, M.M., Noren, D.P., Veirs, V., Emmons, C.K. and Veirs, S. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. J. Acoust. Soc. Am. 125. DOI: 10.1121/1.3040028

Intense levels of sound exposure have caused physical damage to tissues and organs of marine animals[679] [680], and even moderate levels of noise can lead to mortality, with lethal injuries of cetaceans documented in stranded individuals caught up in atypical stranding events[681]. Noise has been shown to cause permanent or temporary loss of hearing in marine mammals and fish. Behavioural responses such as strong avoidance of the sound source can lead to habitat displacement[682]. Some marine animals, such as beaked whales are particularly susceptible to anthropogenic sound, and some populations have experienced declines for years after a sonar-induced stranding event[683]. Short-term effects have been observed in a number of marine mammals and fish but the long-term consequences of chronic noise pollution for individuals and populations are still mainly unknown. Potential long-term impacts of reduced fitness and increased stress leading to health issues have been suggested[684]. There is also growing concern of the cumulative effects of anthropogenic sound and other stressors and how this can affect populations and communities[685].

Research has particularly focussed on cetaceans and other marine mammals such as pinnipeds to a lesser extent but there are still many knowledge gaps that need addressing. Acoustic research for marine fish and invertebrates is still very much in its infancy and requires considerable investment to set up systematic studies of the effects of marine noise on these animals. Consequently many sound-induced impacts for less well-studied taxa are currently potential effects some of which have been inferred from studies of other faunal groups. Substantial further research is required in order to better understand the impacts of anthropogenic sound on marine biodiversity. However, a system of prioritisation will also be needed to focus on species that are already highly threatened or endangered through a combination of multiple stressors and intrinsic characteristics, but also representative groups of understudied taxa such as marine fish and invertebrates.

Mitigation of anthropogenic sound levels in the marine environment require regular updating to keep in touch with changes in acoustic technology and the latest scientific knowledge of marine species such as acoustic sensitivity and population ecology. Activities such as military exercises emitting sonar or seismic surveys using air guns do have mitigation guidelines in place but these can vary considerably between navies or regions and a number of limitations have been identified[686] [687]. There have been calls for the

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[679] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy

[680] Andre et al., 2011. Low-frequency sounds induce acoustic trauma in cephalopods. Front Ecol Environ 9: 489–493,

[681] Fernández, A., Edwards, J.F., Rodríguez, F., Espinosa de los Monteros, A., Herráez, P., Castro, P., Jaber, J.R., Martín, V., and Arbelo, M. 2005. 'Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57

[682] Lusseau, D. 2005. Residency pattern of bottlenose dolphins Tursiops spp. In Milford Sound, New Zealand, is related to boat traffic. Mar. Ecol. Prog. Ser. 295: 265–272

[683] Claridge, D.E. 2006. Fine-scale distribution and habitat selection of beaked whales. M.Sc. thesis, Department of Zoology, University of Aberdeen, Scotland, U.K.

[684] Wright, J.W., Deak, T. and Parsons, E.C.M. 2009. Concerns Related to Chronic Stress in Marine Mammals. IWC SC/61/E16 7 pp.

[685] Wright, A.J. (ed) 2009. Report of the Workshop on Assessing the Cumulative Impacts of Underwater Noise with Other Anthropogenic Stressors on Marine Mammals: From Ideas to Action. Monterey, California, USA, 26th-29th August, 2009. Okeanos - Foundation for the Sea, Auf der Marienhöhe 15, D-64297 Darmstadt. 67+iv p. Available from http://www.okeanos-foundation.org/assets/Uploads/CIReportFinal3.pdf

[686] Weir, C., Dolman, S.J., 2007. Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. Journal of International Wildlife Law and Policy 10, 1–27

setting of global standards for the main activities responsible for producing anthropogenic sound in the oceans. Progress is being made with regard to commercial shipping and quieting but standards for naval sonar or seismic surveys are also required to reduce impacts on marine species.

Mitigation and management of anthropogenic noise through the use of spatio-temporal restrictions of activities has been recommended as the most practical and straightforward approach to reduce effects on marine animals. A framework for the implementation of STR's is available for use by national and regional bodies to ensure that acoustic issues are considered in future marine spatial planning[688].

There are also additional global factors to consider when assessing the potential of anthropogenic noise to affect marine species. It is known that low frequency sound absorption decreases with increasing acidity in seawater. Modelling of projected changes in acidity caused by ocean acidification has suggested that particularly noisy regions that are also prone to reduced sound absorption should be recognised as hotspots where mitigation and management is probably most needed. Further work is required to verify or refute these predictions.

Previously relatively quiet areas of the oceans such as the Arctic are also highly likely to be exposed to increased levels of anthropogenic sound as the sea ice coverage decreases. The 'new waters' will be open to dramatically increased levels of shipping, exploration and exploitation especially by the oil and gas industry (seismic surveys and offshore industry) but also to commercial fishing vessels and possibly naval exercises (active sonar). The effects on marine biodiversity are likely to be significant. Management frameworks for the Arctic need to consider anthropogenic noise as an important stressor alongside others when deciding the extent of activities permitted in these waters.

Anthropogenic sound in the marine environment is an issue that is likely to increase in significance over the next few decades, which could have both short- and long-term negative consequences for marine animals. The uncontrolled introduction of increasing noise is likely to add significant further stress to already-stressed oceanic biota[689]. Protecting marine life from this growing threat will require more effective control of the activities producing sound which depends on a combination of greater understanding of the impacts and also increased awareness of the issue by decision makers both nationally and regionally to implement adequate regulatory and management measures.

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[687] Dolman, S. J., Weir, C.R., and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58 pp. 465-477.

[688] Agardy, T., Aguilar, N., Cañadas, A., Engel, M., Frantzis, A., Hatch, L., Hoyt, E., Kaschner, K., LaBrecque, E., Martin, V., Notarbartolo di Sciara, G., Pavan, G., Servidio, A., Smith, B., Wang, J., Weilgart, L., Wintle, B. and Wright, A. 2007. A Global Scientific Workshop on Spatio-Temporal Management of Noise. Report of the Scientific Workshop. 44 pages. http://www.okeanos-foundation.org/assets/Uploads/str2007en2.pdf

[689] Boyd, I.L., G. Frisk, E. Urban, P. Tyack, J. Ausubel, S. Seeyave, D. Cato, B. Southall, M. Weise, R. Andrew, T. Akamatsu, R. Dekeling, C. Erbe, D. Farmer, R. Gentry, T. Gross, A. Hawkins, F. Li, K. Metcalf, J.H. Miller, D. Moretti, C. Rodrigo, and T. Shinke. 2011. An International Quiet Ocean Experiment. *Oceanography* 24(2):174–181

Annex 1. Overview of observed effects of underwater noise on marine life (adapted from Boyd et al., 2008; OSPAR, 2009)

Note: *Papers cited refer to observed effects to actual anthropogenic noise sources 'in situ' unless otherwise stated in parentheses e.g., modelled. Most laboratory experiments are not included but recordings of anthropogenic noise sources played to marine species at sea are listed as 'simulated' in parentheses*

Impact	**Type of effect**	**Type of Anthropogenic Noise**	**Marine organisms affected**
Physiological Non auditory	Damage to body tissue: e.g., massive internal haemorrhages with secondary lesions, ossicular fractures or dislocation, leakage of cerebro-spinal liquid into the middle ear, rupture of lung tissue	1. Intense low or mid-frequency (Naval) sonar, 2. Seismic air gun arrays, 3. Explosions	1. Beaked whales[690] [691], 2. Giant squid (inferred) [692], 3. Humpback whale[693]
	Induction of gas embolism (Gas Embolic Syndrome, Decompression Sickness/DCS, 'the bends', Caisson syndrome)	Intense mid-frequency (Naval) sonar	Beaked whales[694][695], odontocete cetaceans[696]
	Induction of fat embolism	Intense mid-frequency (Naval) sonar	Beaked whales[697]
	Disruption of gas filled organs such as the swim	Pile driving	Various fish species[698], Chinook Salmon (juvenile)[699]

[690] Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy.

[691] Fernández, A., Edwards, J.F., Rodríguez, F., Espinosa de los Monteros, A., Herráez, P., Castro, P., Jaber, J.R., Martín, V., and Arbelo, M. 2005. 'Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57

[692] Guerra, A and Gonzalez, A.F. 2006. Severe injuries in the *Arhiteuthis dux* stranded after acoustic explorations. In: International Workshop on Impacts of Seismic Survey. Activities on Whales and other Marine Biota. Federal Environment Agency, Dessau, Germany.

[693] Ketten, D.R. (1995). Estimates of blast injury and acoustic zones for marine mammals from underwater explosions. In: Kastelein, R.A., Thomas, J.A., and Nachtigall, P.E. (ed), Sensory Systems of Aquatic Mammals. De Spil Publishers, Woerden, NL, pp: 391-407.

[694] Fernandez et al., 2005. Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57

[695] Hooker et al., 2009. Could beaked whales get the bends?: Effect of diving behaviour and physiology on modelled gas exchange for three species: *Ziphius cavirostris*, *Mesoplodon densirostris* and *Hyperoodon ampullatus*. Resp. Physiol Neurobiol. 137: 235-246

[696] Jepson et al., 2003. Gas-bubble lesions in stranded cetaceans. Nature 425: 575–576.

[697] Fernández et al. 2005. 'Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57

[698] Caltrans. (2004). Fisheries and hydroacoustic monitoring program compliance report for the San Francisco–Oakland bay bridge east span seismic safety project. Caltrans Contract EA12033. San Francisco, CA: Caltrans.

[699] National Cooperative Highways Research Program. 2011. Hydroacoustic impacts on fish from pile installation. NCHRP Project 25-28. Research Results Digest 363 http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rrd_363.pdf

Impact	**Type of effect**	**Type of Anthropogenic Noise**	**Marine organisms affected**
	bladder (fishes) [with consequent damage to surrounding tissue]		
	Endochrinological stress responses	Seismic air guns	Sea bass[700], Atlantic Salmon[701], Bottlenose dolphin and Beluga (simulated)[702]
Auditory (Sound induced hearing loss)	Gross damage to the auditory system e.g., resulting in: rupture of the oval or round window or rupture of the ear drum	1. Intense mid-frequency sonar, 2. Explosions	1. Beaked whales[703], 2. Humpback whale[704]
	Vestibular trauma e.g., resulting in: vertigo, dysfunction of coordination and equilibrium	1. Explosions, 2. Air guns (naval sonar, pile driving, other sonars, drilling)	1. Humpback whale[705], 2. Spotted dolphin[706]
	Damage to the sensory hair cells	Air guns (actual and simulated)	Various fin-fish[707], Pink snapper[708], Cephalopods (four species)[709]
	Permanent hearing threshold shift (PTS) i.e. a permanent	1. Air guns (modelled), 2. Sonar (simulated)	1. Baleen whales[710], 2. Harbour seal[711]

700 Santulli, A., Modica, A., Messina, C., Ceffa, L., Curatolo, A., Rivas, G., Fabi, G., D'Amelio, V. 1999. Biochemical responses of European sea bass (*Dicentrarchus labrax L.*) to the stress induced by offshore experimental seismic prospecting in the mediterranean sea. Marine Pollution Bulletin 38, 105-1114

701 Svedrup, A., Kjellsby, E., Kr uger, P. G., Flùysand, R., Knudsen, F. R., Enger, P. S., Serck-Hanssen, G., Helle, K. B. (1994) E€ects of experimental seismic shock on vasoactivity of arteries, integrity of vascular endothelium and on primary stress hormones of the Atlantic salmon. Journal of Fish Biology 45, 973-995.

702 Romano, T.A. et al. 2004. Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. Can. J. Fish. Aquat. Sci. 61: 1124–1134

703 Evans DL, England GR (2001) Joint interim report Bahamas marine mammal stranding event of 14–16 March 2000. US Department of Commerce and US Navy.

704 Ketten, D.R., Lien, J. & Todd, S. 1993. Blast injury in humpback whale ears: Evidence and implications. J. of the Acoustic Society of America 94: 1849–1850

705 Todd, S., Stevick, P., Lien, J., Marques, F., and Ketten, D. (1996). Behavioural effects of exposure to underwater explosions in humpback whales (*Megaptera novaeangliae*). Can J. Zool., 74: 1661-1672.

706 Gray & Van Waerebeek 2011. Postural instability and akinesia in a pantropical spotted dolphin, S.a., in proximity to operating airguns of a geophysical seismic vessel. J. Nat. Cons.

707 McCauley RD, Duncan AJ, Penrose JD, et al. 2000. Marine seismic surveys – a study of environmental implications. APPEA J 40: 692–706.

708 McCauley, R. D., Fewtrell, J. & Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears. Journal of the Acoustical Society of America 113, 638–642

709 André et al., 2011. Low-frequency sounds induce acoustic trauma in cephalopods. Front Ecol Environ 9: 489–493

710 Gedamke et al. 2011. Assessing risk of baleen whale hearing loss from seismic surveys: the effect of uncertainty and individual variation. JASA 129 (1): 496-506

Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
	elevation of the level at which a sound can be detected		
	Temporary hearing threshold shift (TTS) i.e. a temporary elevation of the level at which a sound can be detected	1. Air guns (modelled), 2. Mid-frequency sonar (simulated), 3. Ice breaker (modelled)	1. Baleen whales[712], Harbour porpoise[713], 2. Bottlenose dolphin[714],, 3. Beluga[715]
Perceptual	Masking of communication with conspecifics	1. Shipping, 2. high-frequency sonar, 3. Recreational vessels, 4. Ice-breaker vessels, 5. Low-frequency sonar	1, Cuvier's beaked whale[716], 3. Delphinid cetaceans[717], Fish: Sciaenid, Pomacentrid and Goby[718], Killer whale (modelled)[719], Pacific humpback dolphin[720]4. Beluga (modelled)[721], 5. Humpback whale[722]
	Masking of other biologically important sounds including orientation and settlement cues,	Shipping	Cuvier's beaked whale[723]

711 Reichmuth 2009 Effects of Noise and Tonal Stimuli on Hearing in Pinnipeds. ONR report, or Kastak et al. 2008. Noise-induced PTS in a harbor seal. JASA 123 (5) p. 2986.

712 Gedamke et al. 2011. Assessing risk of baleen whale hearing loss from seismic surveys: the effect of uncertainty and individual variation. JASA 129 (1): 496-506

713 Lucke, K., Siebert, U., Lepper, P.A., Blanchet, M-A. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. J. Acoust. Soc. Am. 125: 4060-4070.

714 Finneran, J.J., Carder, D.A., Schlundt, C.A. and Ridgway, S.H., 2005. Temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*) exposed to mid-frequency tones. J. Acoust. Soc. Am. 118: 2696-2705

715 Erbe, C. and D. M. Farmer. 2000. Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. Journal Acoustical Society of America 108, 1332-1340.

716 Aguilar Soto, N., N. Johnson, P. T. Madsen, P. L. Tyack, A. Bocconcelli, and J. F. 2006. Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziphius cavirostris*)? Marine Mammal Science 22, 690–699

717 Jensen, F.H., Bedjer. L., Wahlberg, M., Aguilar Soto, N., Johnson, M., Madsen, P.T. 2009. Vessel noise effects on delphinid communication. Mar. Ecol. Prog. Ser. 395: 161-175.

718 Codarin et al., 2009. Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). Mar. Pollut. Bull., doi:10.1016/j.marpolbul.2009.07.011

719 Erbe, C. 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. Marine Mammal Science 18, 394- 418

720 Van Parijs, S.M. and Corkeron, P.J. 2001. Boat trafficaffects the acoustic behaviour of Pacific humpack dolphins, *Sousa chinensis*. J. Mar. Biol. Assoc. U.K. 81: 533-538.

721 Erbe, C. and D. M. Farmer. 2000. Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. Journal Acoustical Society of America 108, 1332-1340.

722 Miller, P.J.O., Biassoni, N., Samuels, A. and Tyack, P.L. 2000. Whale songs lengthen in response to sonar. Nature, 405: 903

723 Aguilar Soto, N., N. Johnson, P. T. Madsen, P. L. Tyack, A. Bocconcelli, and J. F. 2006. Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziphius cavirostris*)? Marine Mammal Science 22, 690–699

Impact	**Type of effect**	**Type of Anthropogenic Noise**	**Marine organisms affected**
	echolocation signals		
Behavioural	Stranding or beaching	Intense low or mid-frequency (Naval) sonar	Beaked whales[724] [725] [726] [727] [728] [729], Short finned pilot whale[730] [731], Pygmy sperm whale[732], Pygmy killer whale[733], Minke whale[734] [735], Hawaiian melon-headed whale[736],
	Behaviour modified (less effective / efficient)	Shipping (simulated)	Sea bass and sea bream[737]
	Behaviourally-mediated	1. Acoustic deterrents, 2. Recreational	1. Harbour porpoise[738] [739] 2. Bottlenose dolphin[740] [741],

[724] Frantzis, A. 1998. Does acoustic testing strand whales? Nature 392: 29.

[725] Balcomb, K. C. III and Claridge, D. E. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. Bahamas Journal of Science 5: 1–12.

[726] Fernández, A., Edwards, J.F., Rodríguez, F., Espinosa de los Monteros, A., Herráez, P., Castro, P., Jaber, J.R., Martín, V., and Arbelo, M. 2005. 'Gas and fat embolic syndrome' involving a mass stranding of beaked whales (family *Ziphiidae*) exposed to anthropogenic sonar signals. Vet. Pathol. 42: 446-57.

[727] Brownell, R. L., Yamada, T., Mead, J. G. and van Helden, A. L. 2004. Mass strandings of Cuvier's beaked whales in Japan: U.S. Naval acoustic link? Paper IWC/SC/56/E37 to 56th meeting of IWC Scientific Committee. 10 pp

[728] Wang, J.W. and Yang, S-C. 2006. Unusual stranding events of Taiwan in 2004 and 2005. J. Cetacean Res. Manage. 8(3): 283–292

[729] Yang, W.-C., Chou, L.-S., Jepson, P. D., Brownell, R. L., Cowan, D., Chang, P. H., Chiou, H.- I., Yao, C.-J., Yamada, T. K., Chiu, J.-T., Wang, P.-J. and Fernández, A. 2008. Unusual cetacean mortality event in Taiwan, possibly linked to naval activities. Veterinary Record 162, 184–186

[730] Ibid

[731] Hohn, A.A., Rotstein, D.S., Harms, C.A., and Southall, B.L. 2006. Report on Marine Mammal Unusual Mortality Event UMESE 0501Sp: Multispecies mass stranding of pilot whales (*Globicephala macrorhynchus*), minke whale (*Balaenoptera acutorostrata*), and dwarf sperm whales (*Kogia sima*) in North Carolina on 15-16 January 2005. Silver Spring: National Marine Fisheries Service. 230 pp.

[732] Ibid

[733] Wang, J.W. and Yang, S-C. 2006. Unusual stranding events of Taiwan in 2004 and 2005. J. Cetacean Res. Manage. 8(3): 283–292

[734] Balcomb, K. C. III and Claridge, D. E. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. Bahamas Journal of Science 5: 1–12

[735] Hohn, A.A., Rotstein, D.S., Harms, C.A., and Southall, B.L. 2006. Report on Marine Mammal Unusual Mortality Event UMESE 0501Sp: Multispecies mass stranding of pilot whales (*Globicephala macrorhynchus*), minke whale (*Balaenoptera acutorostrata*), and dwarf sperm whales (*Kogia sima*) in North Carolina on 15-16 January 2005. Silver Spring: National Marine Fisheries Service. 230 pp

[736] Southall, B.L., Braun, R., Gulland, F.M.D., Heard, A.D., Baird, R.W., Wilkin, S.M., and Rowles, T.K. 2006. Hawaiian melon-headed whale (*Peponacephala electra*) mass stranding event of July 3-4, 2004. Silver Spring: National Marine Fisheries Service. 78 pp.

[737] Buscaino, G. et al. 2009. Impact of an acoustic stimulus on the motility and blood parameters of European sea bass (*Dicentrarchus labrax* L.) and gilthead sea bream (*Sparus aurata* L.). Mar. Environ. Res. 69, 136–142

[738] Kastelein, R.A., Jennings, N., Verboom, W.C., de Haan, D., Schooneman, N.M. 2006. Differences in the responses of a striped dolphin (*Stenella coeruleoalba*) and a harbour porpoise (*Phocoena phocoena*) to an acoustic alarm. Mar. Enviro. Res. 61: 363-378.

Impact	**Type of effect**	**Type of Anthropogenic Noise**	**Marine organisms affected**
	effects including avoidance,	vessels, 3. Over flying aircraft, 4. Explosions, 5. Bottom towed fishing gear, 6. Drilling, 7. Dredging, 8. High-frequency sonar, 9. Intense low or mid-frequency sonar, 10. Air guns, 11. Pile driving, 12 Icebreakers	Bluefin tuna[742], Killer whale[743], Humpback whale[744] 9. Killer whales[745], Hooded seals[746], Gray Whales[747] 10. Bowhead whales[748], humpback whales, turtles, fish and squid[749], Pelagic fish – herring, blue whiting and others[750], Various Cetaceans[751], 11. Cod and sole[752], Harbour porpoises[753]12. Beluga[754]

[739] Olesiuk, P.F., Nichol, L.M., Sowden, M.J., and Ford, J.K.B. 2002. Effect of the sound generated by an acoustic harassment device on the relative abundance and distribution of harbor porpoises (Phocoena phocoena) in Retreat Passage, British Columbia. Mar. Mamm. Sci. 18: 843-862.

[740] Goodwin, L., and Cotton, P.A. 2004. Effects of boat traffic on the behavior of bottlenose dolphins (*Tursiops truncatus*). Aq. Mammals 30: 279-283

[741] Lemon, M., Lynch, T.P., Cato, D.H., and Harcourt, R.G. 2006. Response of travellingbottlenose dolphins (*Tursiops aduncus*) to experimental approaches by a powerboat in Jervis Bay, New South Wales, Australia. Bio. Conserv. 127: 363-372.

[742] Sarà et al., 2007. Effect of boat noise on the behaviour of Bluefin tuna *Thunnus thynnus* in the Mediterranean Sea. Mar. Ecol.-Prog. Ser. 331, 243–253

[743] Noren, D.P., Johnson, A.H., Rehder, D., Larson, A. 2009. Close approaches by vessels elicit surface active behaviors by southern resident killer whales. Endangered Species Res. 8: 179-192.

[744] Au, W. W. L. and M. Green, M. 2000. Acoustic interaction of humpback whales and whale-watching boats. Marine Environmental Research 49, 469-481

[745] Kvadsheim, P., Benders, F., Miller, P., Doksaeter, L., Knudsen, F., Tyack, P., Nordlund, N., Lam, F.-P., Samarra, F., Kleivane, L., and Godø, O.R. 2007. Herring (sild), killer whales (spekkhogger) and sonar – the 3S-2006 cruise report with preliminary results. Norway: Norwegian Defence Research Establishment. 79 pp.

[746] Kvadsheim, P.H. et al. 2010. Effects of naval sonar on seals. Norwegian Defence Research Establishment (FFI). FFI-rapport 2010/02222. 26 pp.

[747] Tyack, P and Clark, C., 1998. Quicklook Phase II, Playback of Low-Frequency Sound to Gray Whales Migrating Past the Central California Coast. Quicklook Report pp. 1-34.

[748] Ljungblad, D.K., Würsig, B., Swartz, S.L., and Keene, J.M. 1988. Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea. Arctic 41(3): 183-194

[749] McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M.-N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J., McCabe K. 2000. Marine seismic surveys: Analysis and propagation of air-gun signals; and effects of air-gun exposure on humpback whales, sea turtles, fishes and squid. Western Australia: Curtin University of Technology. 203 pp.

[750] Slotte, A., Hansen, K., Dalen, J., and One, E. 2004. Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. Fish. Res. 67: 143-150.

[751] Stone, C.J., and Tasker, M.L. 2006. The effects of seismic airguns on cetaceans in UK waters. J. Cetacean Res. Manage. 8: 255-263.

[752] Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D.T. & Thomsen, F. (2010) Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report

[753] Thomsen, F., Lüdemann, K., Kafemann, R. and Piper, W. 2006. Effects of offshore wind farm noise on marine mammals and fish, biola, Hamburg, Germany on behalf of COWRIE Ltd

[754] Finley KJ, Miller GW, Davis RA, Greene CR (1990) Reactions of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, to ice-breaking ships in the Canadian high arctic. Canadian Bulletin of Fisheries and Aquatic Science 224:97-117

Impact	**Type of effect**	**Type of Anthropogenic Noise**	**Marine organisms affected**
	Adaptive shifting of vocalisation intensity and/or frequency including cessation of calls	1. Shipping, 2. Recreational vessels, 3. Air guns, 4. Intense low or mid-frequency sonar, 5. Acoustic devices. 6. Acoustic experiments	1. Right whale[755], 2. Killer whale[756], Beluga[757], Fin whale[758], 3. Sperm whale[759], Fin whale[760] 4. Long finned pilot whale[761], Blue and fin whale[762], Humpback whale[763] [764], Sperm whale[765], Blainville's beaked whales[766], 5. Sperm whale[767], 6. Humpback whale[768]

[755] Parks, S.E., Clark, C.W., and Tyack, P.L. 2007. Short- and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication. J. Acoust. Soc. Am. 122: 3725-3731.

[756] Holt, M.M., Noren, D.P., Veirs, V., Emmons, C.K., and Viers, S. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. J. Acoust. Soc. Am. 125: EL27-32.

[757] Lesage, V., Barrette, C., Kingsley, M.C.S., and Sjare, B. 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. Mar. Mamm. Sci. 15: 65-84

[758] Watkins, W. W. 1986. Whale reactions to human activities in Cape Cod waters. Marine Mammal Science 2: 251-262.

[759] Bowles, A.E., Smultea, M., Würsig, B., DeMaster, D.P., and Palka, D. 1994. Relative abundance and behavior of marine mammals exposed to transmissions from the Heard Island Feasibility Test. J. Acoust. Soc. Am. 96: 2469-2484.

[760] International Whaling Commission Scientific Committee (IWC/SC). 2007. Report and Annex K of the 2007 Scientific Committee Report: Report of the Standing Working Group on Environmental Concerns. J. Cetacean Res. Manag. 9 (Suppl.): 227-296

[761] Rendell, L.E., and Gordon, J.C.D. 1999. Vocal responses of long-finned pilot whales (*Globicephala melas*) to military sonar in the Ligurian Sea. Mar. Mammal Sci. 15: 198-204

[762] Clark, C.W., Tyack, P. and Ellison, W.T. 1998. Quicklook. Low-Frequency Sound Scientific Research Program, Phase I: responses of blue and fin whales to SURTASS LFA

[763] Clark, C.W. and Tyack, P. 1998. Quicklook, Low-Frequency Sound Scientific Research Program, Phase III: responses of humpback whales to SURTASS LFA off the Kona Coast, Big Island, Hawaii.

[764] Miller, P.J.O., Biassoni, N., Samuels, A. and Tyack, P.L. 2000. Whale songs lengthen in response to sonar. Nature, 405: 903

[765] Watkins, W.A., Moore, K.E., and Tyack, P. 1985. Sperm whale acoustic behaviors in the southeast Caribbean. Cetology 49: 1-15

[766] McCarthy E, Moretti D, Thomas L, DiMarzio N, Morrissey R, Jarvis S, Ward J, Izzi A, Dilley A (2011) Changes in spatial and temporal distribution and vocal behavior of Blainville's beaked whales (*Mesoplodon densirostris*) during multiship exercises with mid-frequency sonar. Marine Mammal Science

[767] Watkins, W.W. and Schevill, W.E. 1975. Sperm whales (*Physeter catodon*) react to pingers. Deep Sea Research 22 : 123-129.

[768] Risch D, Corkeron PJ, Ellison WT, and Van Parijs SM. 2012. Changes in humpback whale song occurrence in response to an acoustic source 200 km away. PLoS ONE 7(1): e29741. doi:10.1371/journal.pone.0029741

	Interruption of normal behaviour such as feeding, breeding or nursing	1. Recreational or other vessels, 2. Air guns, 3. intense low or mid-frequency sonar, (drilling, explosions, dredging, high-frequency sonar, pile driving, shipping)	1. Killer whale[769], Manatee[770], Damselfish[771], Cuvier's beaked whale[772], 2. Sperm whale[773] [774], 3. Blainville's beaked whales[775]
	Short-term or long-term displacement from area (habitat displacement)	1. tourism vessels, 2. Acoustic deterrents, 3. Shipping and/or drilling (Bottom-towed fishing gear, dredging, air guns)	1. Bottlenose dolphin[776], 2. Killer whale[777], 3. Gray whale [778], Bowhead whale[779]

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[769] Lusseau, D., Bain, D.E., Williams, R., and Smith, J.C. 2009. Vessel traffic disrupts the foraging behavior of southern resident killer whales *Orcinus orca*. Endang. Species Res. 6: 211-221.

[770] Miksis-Olds, J.L., Donaghay, P.L., Miller, J.H., Tyack, P.L., and Nystuen, J.A. 2007. Noise level correlates with manatee use of foraging habitats. J. Acoust. Soc. Am. 121: 3011-3020.

[771] Picciulin et al., 2010. *In situ* behavioural responses to boat noise exposure of *Gobius cruentatus* (Gmelin, 1789; fam. Gobiidae) and *Chromis chromis* (Linnaeus, 1758; fam. Pomacentridae) living in a Marine Protected Area. Journal of Experimental Marine Biology and Ecology 386: 125–132

[772] Aguilar Soto, N., N. Johnson, P. T. Madsen, P. L. Tyack, A. Bocconcelli, and J. F. 2006. Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziphius cavirostris*)? Marine Mammal Science 22, 690–699

[773] International Whaling Commission Scientific Committee (IWC/SC). 2007. Report and Annex K of the 2007 Scientific Committee Report: Report of the Standing Working Group on Environmental Concerns. J. Cetacean Res. Manag. 9 (Suppl.): 227-296

[774] Miller, P.J.O., Johnson, M., Madsen, P.T., Quero, M.E., Biassoni, N. & Tyack, P. 2006: At-sea experiments indicate that airguns affect the foraging behaviour of sperm whales in the Gulf of Mexico. IWC-SC/58/ForInfo2. 34 pp

[775] Tyack PL, Zimmer WMX, Moretti D, Southall BL, Claridge DE, et al. 2011. Beaked Whales Respond to Simulated and Actual Navy Sonar. PLoS ONE 6(3): e17009. doi:10.1371/journal.pone.0017009

[776] Lusseau, D. 2004. The hidden cost of tourism: Detecting long-term effects of tourism using behavioral information. Ecol. & Soc. 9: 2

[777] Morton, A.B., and Symonds, H.K. 2001. Displacement of Orcinus orca (L.) by high amplitude sound in British Columbia. ICES J. Mar. Sci. 59: 71-80.

[778] Bryant, P.J., Lafferty, C.M., and Lafferty, S.K. 1984. Reoccupation of Laguna Guerrero Negro Baja California, Mexico, by gray whales. Pp. 375-386 in M.L. Jones, S.L. Swartz, and S. Leatherwood (eds.). The Gray Whale *Eschrictius robustus*. Orlando: Academic Press.

[779] Schick, R.S., and Urban, D.L. 2000. Spatial components of bowhead whale (*Balaena mysticetus*) distribution in the Alaskan Beaufort Sea. Can. J. Fish. Aquat. Sci. 57: 2193-2200.