Advance draft of information document for SBSTTA 20 (agenda item 4.3) for Peer-Review

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

1. At its tenth meeting in 2010, the Conference of Parties to the Convention on Biological Diversity requested the Executive Secretary of the CBD to compile and synthesize available scientific information on anthropogenic underwater noise and its impacts on marine and coastal biodiversity and habitats (decision X/29). The initial draft (UNEP/CBD/SBSTTA/16/INF/12) of this document was submitted, as information, to the sixteenth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA 16), and the eleventh meeting of the Conference of the Parties to the Convention.

2. The Conference of the Parties, at eleventh meeting, welcomed this synthesis, and encouraged Parties, other Governments and relevant organizations to promote research and awareness on the impacts of anthropogenic underwater noise on marine and coastal biodiversity, to take measures to mitigate these impacts and to develop indicators and explore frameworks for monitoring underwater noise for the conservation and sustainable use of marine biodiversity. At this meeting, COP also requested the Executive Secretary to organize an expert workshop with a view to improving and sharing knowledge on underwater noise and its impacts on marine and coastal biodiversity, and to develop practical guidance and toolkits to minimize and mitigate the significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, including marine mammals, in order to assist Parties and other Governments in applying management measures (decision XI/18).

3. Pursuant to this request, the Executive Secretary convened an Expert Workshop on Underwater Noise and its Impacts on Marine and Coastal Biodiversity at the headquarters of the International Maritime Organization, London, from 25 to 27 February 2014. This workshop focused on improving and sharing knowledge on underwater noise and its impacts on marine and coastal biodiversity, and discussed practical guidance and toolkits to minimize and mitigate the significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, including marine mammals, in order to assist Parties and other Governments in applying management measures, as appropriate.

4. A revised version of the information document (UNEP/CBD/SBSTTA/16/INF/12) was made available at the above-mentioned workshop to support the workshop discussions. Following the workshop, the document was further revised and updated, incorporating comments and suggestions received from workshop participants, through a consultancy commissioned by the Secretariat, with the generous support of the European Commission.

5. This updated information document therefore is being made available for peer-review by Parties, other Governments and relevant organizations.

6. Upon further revision incorporating peer-review comments, this document will be submitted as information to the Subsidiary Body at its twentieth meeting and will be published as a report in the CBD Technical Series in due course.

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EXECUTIVE SUMMARY

Introduction and Background

Anthropogenic noise in the marine environment has increased markedly over the last 100 or so years as human use of the oceans has grown and diversified. Technological advances in vessel propulsion and design and the increasing and diversified human 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 increased, which has been primarily attributed to commercial shipping noise. The last half century has seen an expansion of industrial activities in the marine environment, including commercial shipping, oil and gas exploration and production, commercial fishing and, more recently, the development of offshore renewable energy. In coastal areas, such as partially enclosed bays, harbours and estuaries, small vessels are becoming an increasingly dominant part of coastal acoustic environments.

Anthropogenic noise has gained recognition at multiple levels as an important stressor for marine biodiversity. The impacts of sound on marine mammals have received notable attention, especially impacts from military use of active sonar, and industrial seismic surveys that seem to coincide 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 global level with recognition by a number of international and regional agencies, commissions and organisations.

Sound is a mechanical disturbance that travels through an elastic medium (e.g., air, water or solids). **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, thereby enabling long distance communication, but also a long range of noise impact on aquatic animals. 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 received by an animal is subject to propagation conditions that can be quite complex, which can in turn significantly affect how the sound energy is received by an animal.

Natural and Anthropogenic Underwater Sound

There are a range of natural sound sources in the marine environment from physical and biological origins. Natural physical phenomena that contribute to underwater ambient noise include wind, waves and swell patterns; bubbles; currents and turbulence; earthquakes; precipitation and ice. Marine mammals (cetaceans and pinnipeds) produce sounds that are used for communication, orientation,navigation and foraging. Many marine fish species produce sound for communication, either as individuals, but also as groups. Different types of invertebrates also contribute to ambient noise, particularly in tropical or sub-tropical reef environments, including snapping shrimp, squid, crabs, lobsters and urchins.

The underwater world is subject to a wide range of man-made noise from activities such as commercial shipping, oil and gas exploration and 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 certain activities (e.g., shipping or construction). Anthropogenic noise can be broadly split into two main types: impulsive and non-impulsive sounds. Examples of impulsive sounds are those from explosions, airguns or impact pile driving, while non-impulsive sounds result from activities such as shipping, construction (e.g., drilling and dredging), or renewable energy operations.

The Importance of Sound to Marine Animals

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 preferred sensory medium for many marine animals.

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

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 habitat selection, 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 sound. However, the importance of sound for many marine taxa is still rather poorly understood and in need of further investigation.

The Impacts of Underwater Noise on Marine Biodiversity

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

A wide range of effects of increased levels of sound on marine fauna have been documented, both in laboratory and field conditions. However there are still many gaps and uncertainties in our understanding of noise effects on marine fauna. The known 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, impeding functions such as the ability to efficiently feed. Masking of important acoustic signals or cues can impact communication among conspecifics and may interfere with larval orientation, which could have implications for recruitment. Some marine mammals have tried to compensate for elevated background noise levels by changing 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 . Lower noise 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 impacts from anthropogenic noise, and some populations have experienced declines for years after a sonar-induced stranding event.

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 largely unknown. Potential long-term impacts of reduced fitness and increased stress leading to health issues have been suggested. There is also growing concern regarding 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.

Acoustic Research and Future Research Needs

Previous acoustic research for marine fauna has particularly focused on cetaceans and, to a lesser extent, other marine mammals such as pinnipeds, but there are still many knowledge gaps. Acoustic research for marine fish and invertebrates is still very much in its infancy and requires systematic studies of the effects of marine noise on these animals. Many of the potential effects of anthropogenic underwater noise for less well-studied taxa have been inferred from studies of other faunal groups.

Research needs can be split into four main areas: (1) Further characterization of underwater noise and properties of emitted sound in a changing marine environment; (2) Baseline data on the biology, distribution, abundance and behaviour of marine species; (3) Detailed information on the impacts of sound on marine animals at the individual, population and ecosystem level; and (4) Assessment and improvement of mitigation measures.

Research is required to better understand the impacts of anthropogenic sound on marine biodiversity. The lack of scientific knowledge regarding anthropogenic underwater noise is also currently one of the most important limitations for effective management. There are high levels of uncertainty for noise effects on all marine taxa. There is a need to consolidate knowledge and conduct further detailed research on noise effects on species, populations, habitats and ecosystems in addition to cumulative effects of other stressors.

Identified 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 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. Impacts of anthropogenic noise on commercial fisheries should also be assessed.

New Challenges

New challenges, such as global changes in ocean parameters (e.g., acidity and temperature), are also likely to have consequences for underwater noise levels at a range of geographic scales through changes in sound absorption. The retreat of Arctic sea ice, opening up waters for exploration and resource extraction, also presents important noise-related considerations, as previously relatively quiet areas of the oceans are highly likely to be exposed to increased levels of anthropogenic noise, with potentially significant effects on marine biodiversity.

1. BACKGROUND AND INTRODUCTION

Anthropogenic noise in the marine environment has increased markedly over the last century as human use of the oceans has expanded and diversified.[1,2] Technological advances in vessel propulsion and designand the increasing and diversified human 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 increased in certain areas over the last 50 years, which has been primarily attributed to noise from commercial shipping.[3,4] As well as an increase in commercial shipping, the last half century has also seen an expansion of other 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, such as partially enclosed bays, harbours and estuaries, the rising number of small vessels is are becoming an increasingly dominant part of coastal acoustic environments.[5]

Anthropogenic noise has gained global recognition as an important stressor for marine biodiversity. Initial concerns of the potential negative effects of anthropogenic noise on marine biodiversity were raised by the scientific community in the 1970's and research on the subject expanded in the 1980's.[6] The impacts of sound on marine mammals have received particular attention, especially impacts from the military's use of active sonar, and industrial seismic surveys coincident with cetacean mass stranding events.[7,8] 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 (see Chapter 4 for references).

The issue of underwater noise and its effects on marine biodiversity has also received increasing attention at the international level, with recognition by a number of regional and international bodies, inclduing yhe 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).

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.[9] Human activity in the marine environment is an important component of oceanic background sound.[10] and can dominate the acoustic

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

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

[3] 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

[4] 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

[5] 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

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

[7] 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.

[8] 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

[9] Ibid.

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

spectrum of coastal waters and shallow seas. Although there is a continuum of sound characteristics, man-made noise can be broadly split into two main types: impulsive and non-impulsive sounds. Examples of impulsive sounds are those from explosions, airguns, navigation (depth-finding) sonar or impact pile driving, while non-impulsive sounds result from activities such as shipping, construction (e.g., drilling and dredging), or renewable energy operations. At certain distances from the source, lower frequency impulsive sounds can "smear" and become non-impulsive. 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[11]. In combination with other stressors,underwater noise pollution is likely to contribute to marine defaunation, which is predicted to increase as human use of the oceans industrialises.[12]

Sound is extremely important to many marine animals enabling them to detect the 'acoustic scene' and collect information about their environment. Sound plays a key role in communication, navigation, orientation, feeding and the detection of predators and hazards.[13] Almost all marine vertebrates rely to some extent on sound for these biological functions. Marine mammals use sound as a primary means for underwater communication and sensing. Underwater sound is especially important for Odontocete cetaceans that have developed sophisticated echolocation systems to detect, localise and characterise underwater objects,[14] for example, in relation to feeding behaviour. However, the use of sound is also extremely important for a wide range of animals during different parts of their life-history stages.

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.[15,16] Although the study of invertebrate sound detection is still very limited, it is becoming clearer that many marine invertebrates are sensitive to sounds and related stimuli. However, the importance of sound for many marine taxa is still poorly understood and in need of considerable further investigation.

A variety of marine animals are known to be affected by anthropogenic noise. Negative impacts for at least 55 marine species (cetaceans, teleost fish, marine turtles and invertebrates) have been reported in scientific studies. However, other studies have also reported no effects of noise on certain marine taxa. A wide range of effects of increased levels of sound on marine taxa 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 marine animals. However, as sound levels increase, the elevated background noise can disrupt normal behaviour patterns potentially leading to less efficient feeding, for example. Masking of important acoustic signals or cues can interfere with communication between conspecifics[17] and may interfere with larval orientation which could have implications for recruitment, although further research is required to verify the latter.

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[11] 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

[12] McCauley, D.J., Pinsky, M.L., Palumbi, S.R. et al. 2015. Marine defaunation: Animal loss in the global ocean. Science 347. Doi: 10.1126/science.1255641

[13] 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 p.

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

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

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

[17] 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

Research is illuminating some of the less obvious behavioural effects of noise on aquatic animals (e.g., stress responses,[18,19,20] communication masking,[21,22] cognitive bias, fear conditioning, and attention and distraction[23]), but we still have very limited knowledge and understanding of how these effects influence overall impacts on populations. In addition, very little is known about cumulative effects on marine fauna or their recovery from such effects. Most of the existing mitigation measures are not very effective in reducing possible cumulative and synergistic impacts on marine fauna.[24] They also do not fully consider the exposure context of individuals and how a combination of acute and chronic noise can interact with animal condition to elicit a behavioural response,[25] particularly in marine mammals.

Moreover, a behavioural response is not necessarily the most reliable measure of a population consequence, as harmful impacts can occur without any visible change in behaviour in some species and situations.[26] Animals do not always react in an observable or obvious manner even if they are seriously impacted. Individuals with lower energy reserves or no alternative habitat cannot afford to flee repeatedly from disturbance but are forced to remain and continue feeding, apparently unresponsive to disruption.[27]

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 substantial gaps in our knowledge of underwater noise and the impacts it has on marine species and populations.

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[19] 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.

[20] 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

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

[22] Codarin, A., 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

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[24] Wright, A.J. 2014. Reducing impacts of human ocean noise on cetaceans: Knowledge gap analysis and recommendations. WWF International, Gland, Switzerland

[25] Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S. 2011. A new context-based approach to assess marine mammal behavioural responses to anthropogenic sounds. Conservation Biology

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Underwater Noise and the Convention on Biological Diversity

At its tenth meeting in 2010, the Conference of Parties to the Convention on Biological Diversity requested the Executive Secretary of the CBD to compile and synthesize available scientific information on anthropogenic underwater noise and its impacts on marine and coastal biodiversity and habitats. This draft report was submitted for consideration to the 16th meeting of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA 16) and the 11th meeting of the Conference of the Parties to the Convention. .

The Conference of the Parties welcomed this synthesis, and e*couraged* Parties, other Governments and relevant organizations to promote research and awareness on the impacts of anthropogenic underwater noise on marine and coastal biodiversity, to take measures to mitigate these impacts and to develop indicators and explore frameworks for monitoring underwater noise for the conservation and sustainable use of marine biodiversity. At this meeting, COP also requested the Executive Secretary to organize an expert workshop with a view to improving and sharing knowledge on underwater noise and its impacts on marine and coastal biodiversity, and to develop practical guidance and toolkits to minimize and mitigate the significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, including marine mammals, in order to assist Parties and other Governments in applying management measures.

Pursuant to this request, the Executive Secretary convened an Expert Workshop on Underwater Noise and its Impacts on Marine and Coastal Biodiversity at the headquarters of the International Maritime Organization, London, from 25 to 27 February 2014. This workshop focused on improving and sharing knowledge on underwater noise and its impacts on marine and coastal biodiversity, and discussed practical guidance and toolkits to minimize and mitigate the significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, including marine mammals, in order to assist Parties and other Governments in applying management measures, as appropriate.

At its twelfth meeting in 2014, the COP welcomed the report of the expert workshop, and en*couraged* Parties and other Governments as well as indigenous and local communities and other relevant stakeholders, to take appropriate measures to avoid, minimize and mitigate the potential significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity, and noted specific approaches and actions, in this regard. COP also i*nvited* competent intergovernmental organizations, including the International Maritime Organization, the Convention on the Conservation of Migratory Species of Wild Animals, and the International Whaling Commission, to take measures within their mandates, and to assist States in taking measures.

A revised version of the information document (UNEP/CBD/SBSTTA/16/INF/12) was made available at the above-mentioned workshop to support the workshop discussions. Following the workshop, the document was further revised and updated, incorporating comments and suggestions received from workshop participants, through a consultancy commissioned by the Secretariat, with the generous support of the European Commission.

2. UNDERWATER SOUND: CHARACTERISTICS, RELEVANCE AND TRENDS

OVERVIEW OF UNDERWATER SOUND

Sound is a mechanical disturbance that travels through an elastic medium (e.g., air, water or solids).[28] Sound is created when particles in an elastic medium are displaced by an external force and oscillate. 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 (kilohertz), 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). 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,[29] thereby enabling long distance communication, but also a long-distance impact of noise on aquatic animals.[30] Sound propagation is affected by three 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.[31]

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.[32] Sound pressure levels above water are referenced to 20 µPa, while underwater they are referenced to 1 µPa.[33] There are different measurements and units to quantify the amplitude and energy of the sound pressure level[34,35,36]:

- **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 root-mean-square 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

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

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

[30] 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.

[31] 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

[32] 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

[33] 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)

[34] 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.

[35] 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.

[36] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

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. 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,[37] 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.[38]
- **Rise time** is the time from the start of a sound to its peak pressure, in milliseconds, or the rate of increase to this peak pressure (decibels/second).
- **Duty cycle** is the proportion of time that the sound is 'on', for example, a sound consisting of one 300 ms long pulse every second has a 30% duty cycle.

There is currently no scientific consensus regarding the means to express 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 to allow comparison between measurements.[39] RMS values are useful for relatively long sounds but less effective for brief sounds such as pile-driving strikes and echolocation clicks of whales.[40] Peak-to-peak values in the amplitude waveform provide an alternative measure, but comparisons between peak-to-peak and RMS levels are difficult.[41]

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 that interferes with the detection of other sounds of interest[42]. 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[43].

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[38] Urick, R.J. 1983. Principles of Underwater Sound. McGraw-Hill Co, New York.
[39] 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
[40] 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.
[41] 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
[42] Hawkins, A.D., Pembroke, A.E. and Popper, A.N. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fisheries. 25: 39-64.
[43] 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

Noise is also used in some cases to describe background levels of sound in the sea, including the naturally occurring and spatially uniform sounds generated by various biological sources, weather events, and/or physical phenomena that cannot be entirely assigned to individual sources.[44] Underwater sound is comprised of three components[45]:

- Geophony – sounds produced by the physical environment (e.g. wind, waves, tidal actions, ice , lightning strikes, earthquakes);
- Biophony – sounds produced by non- human organisms (e.g. fishes, marine mammals, invertebrates); and
- Anthrophony – sounds that result from human activity (or produced by humans).

In addition, a 'soundscape' has been defined as the 'collection of biological, geophysical and anthropogenic sounds that emanate from a landscape and which vary over space and time reflecting important ecosystem processes and human activities'.[46] However in the marine context it is the collection of sounds in an underwater landscape or 'seascape'.

NATURAL UNDERWATER SOUND

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 and sub-sea volcanic eruptions; lightning strikes; precipitation and ice cover and activity (movement of ice sheets or icebergs that cause the release of energy as sound).[47] 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.[48] 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[49] while precipitation can raise ambient noise levels by up to 35 dB across a broad band of frequencies (100 Hz to more than 20 kHz).[50] 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.[51]

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.[52] 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.[53] Baleen

[44] Hawkins, A.D., Pembroke, A.E. and Popper, A.N. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fisheries. 25: 39-64

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[46] Pijanowski, B.C. et al. 2011. What is soundscape ecology? An introduction and overview of an emerging new science. Landscape Ecol. DOI 10.1007/s10980-011-9600-8.

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[48] 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.

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whales use low frequency sound for long distance communication[54] over hundreds of kilometres.[55,56] 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.[57] 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.[58] Many marine fish species produce sound for communication.[59] The low frequency sounds created by fish can make a significant contribution to ambient noise.[60] Fish can produce sounds as individuals, but also in choruses[61] and the increase in low-frequency noise can be as much as 20 - 30 dB in the presence of chorusing fishes.[62] 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.[63] In addition to shrimp, a number of other invertebrates contribute to ambient reef noise, including squid,[64] crabs,[65] lobsters[66] and urchins,[67]. Urchins, for example, produce dawn and dusk choruses of feeding noises which are amplified by their skeletons.

THE IMPORTANCE OF SOUND FOR MARINE ORGANISMS

Sound is an important sensory modality for many marine animals.[68] 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. Underwater sound around marine species can be called their "soundscape" and provides animals with sensory information about the surrounding marine environment in three dimensions. 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.[69,70] Sound is particularly important since it provides information from distances well beyond any visual range. As well as detecting sounds, the ability to use information about

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

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

[63] Ibid

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[69] 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

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

the soundscape also requires that an organism is able to discriminate among acoustic signals, determine the location of the sound source (localisation), and perceive biologically important sounds in the presence of 'masking sounds' Although communication among organisms is an important use of sound, detection of the overall soundscape is of great importance. Disrupting the ability to hear and use the soundscape has the potential to affect the fitness and survival of an individual. If a sufficient number of individuals or significant parts of their habitat are affected, then adverse effects could occur at the population scale.

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[71]. 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.[72] While the ears of mammals primarily sense pressure changes, the sensory systems of fish and invertebrates can also sense movement of particles directly[73,74]. Baleen whales, most fishes, sea turtles, and invertebrates hear best at lower frequencies, while for the dolphins and porpoises (based on those species that have been studied) can hear ultrasonic frequencies above human hearing range.[75,76,77,78,79]

Marine mammals use sound as a primary means for underwater communication and sensing.[80] 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.[81] Underwater sound is especially important for odontocete cetaceans that have developed sophisticated echolocation systems to detect, localise and characterise underwater objects,[82] for example, in relation to coordinated movement between conspecifics and feeding behaviour.

Fish utilize sound for navigation and selection of habitat, mating, predator avoidance and prey detection and communication.[83] Impeding the ability of fish to hear biologically relevant sounds might interfere with these critical functions and use of the 'acoustic scene' or 'soundscape'[84] to learn about the overall environment.[85] Larval stages of coral reef fish can detect and are attracted to the sound of coral reefs

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[81] 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

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

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[85] 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

thereby using reef noise as an acoustic cue for orientation.[86] Although the study of invertebrate sound detection is still rather limited, many species have mechano-sensors that have some resemblance to vertebrate ears[87] and, based on the information available, it is becoming clear that many marine invertebrates are sensitive to sounds and related stimuli.[88] This has been demonstrated in tropical waters where crustacean and coral larvae can respond to acoustic cues (reef noise).[89,90] Research is also showing that different habitats within shallow coastal environments can be characterised by the acoustic signals that they produce[91] and that juvenile fish can use these signals to detect different habitats within coral reefs.[92] Settlement-stage coastal crab species are also able to interpret and show a strong settlement and metamorphosis response to habitat-related differences in natural underwater sound.[93]

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.[94] During this time, the oceans have become more industrialised and noise levels associated with human activities have increased.[95] Long-term measurements of ocean ambient sound have revealed that low frequency anthropogenic noise has been increasing in the North Pacific (Figure 1) and Indian Oceans and has been primarily attributed to commercial shipping noise.[96,97,98] Combining this information with data from other studies,[99] it has been suggested that, globally, low frequency ambient noise has increased by at least 20 dB from pre-industrial conditions to the present,[100] although the rate of increase has slowed in some regions in the last decade.[101] 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 factor of six.[102] The world commercial fleet has doubled since 2001 and reached 1.63 billion dead-weight tons by January 2013.[103] In terms of the volume of cargo transported by sea, this figure has been approximately doubling every 20 years.[104] As well, as an increase in commercial

[86] 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

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[96] 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

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[103] UNCTAD, 2013 - Review of Maritime Transport 2013 - Trade Logistics Branch of the Division on Technology and Logistics, UNCTAD.

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

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 and deep sea mining.

In coastal areas, such as partially enclosed bays, harbours and estuaries, small vessels are becoming an increasingly dominant part of coastal acoustic environments.[105] 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.

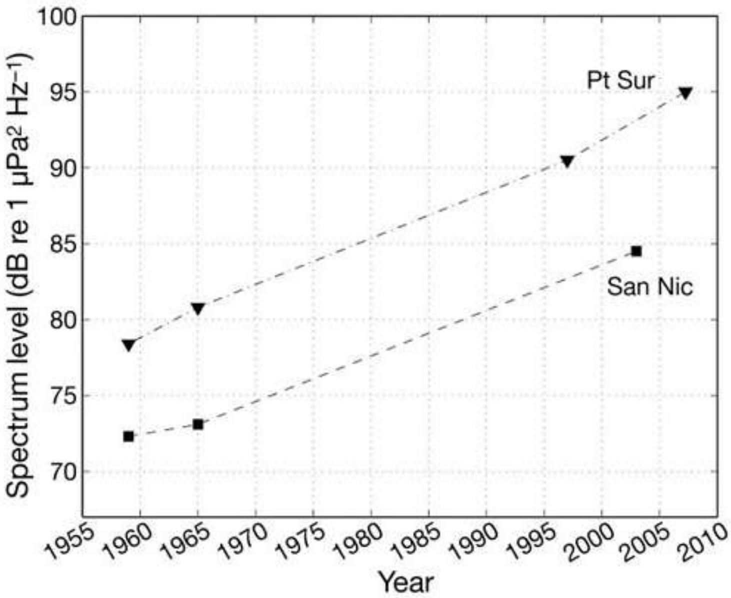

Figure 1. Historical ambient noise data from the North-eastern Pacific at 40 Hz suggest an increase of about 3 dB decade^{-1} averaged over the past 40 years. Data from the United States Navy hydrophone arrays near Point Sur and San Nicolas Island[106, 107, 108] and from recent measurements at these sites (Adapted from Hildebrand, 2009).[109,110,111]

[105] 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

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[111] 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

3. SOURCES AND TYPES OF UNDERWATER ANTHROPOGENIC NOISE

Human activity in the marine environment is an prominent component of oceanic background noise[112] 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).[113] 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-P	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
Tidal and wave energy	165 – 175 rms	10 – 50 000	-	CW	Omni

[112] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[113] 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.

At the source, anthropogenic noise can be broadly split into two main types: impulsive and non-impulsive sounds.[114] 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.[115] 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.[116] 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[117,118] and also of the acoustic and other characteristics of each source[119,120,121]. 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.[122] 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 and 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).[123]

INDUSTRIAL ACTIVITIES

Industrial activities include pile driving, dredging, cable laying, drilling, the construction and operation of offshore wind farms and hydrocarbon production facilities.[124] These activities typically produce noise that has the most energy at low frequencies (20 – 1000 Hz).[125]

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.[126] Source levels can vary depending on the diameter of the pile and the method of pile driving (impact or

[114] Ibid

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

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

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[118] 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

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

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

[121] 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

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

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

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

vibropiling) and can reach 250 dB re 1 μPa peak to peak at 1m.[127] 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)[128] with the main frequency content below 100 Hz.[129] Noise from fixed drilling platforms is slightly lower; e.g., 115 - 117 dB re 1 μPa at 405 and 125 metres respectively[130]. 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).[131] The ships use thrusters to remain in position, resulting in a mixture of propeller and drilling noise.[132]

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.[133] Measurements of the sound spectrum levels emitted by an aggregate dredger show that most energy was below 500 Hz.[134]

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.[135] 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.[136] Noise produced during operations has been measured from single turbines (maximum power 2 MW) by studies between 1994 and 2004.[137] Most of the sound generated was pure tones below 1 kHz, and mainly below 700Hz.[138] Data collected from Utgrunden, Sweden in 2005 revealed that 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.[139] More recent measurements on four offshore wind farms around the UK in 2005 and 2007 (2 - 3 MW) confirmed rather low broadband received sound pressure levels (114 - 130 dB re 1 μPa) inside wind farm areas with a

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

[128] The term moderate refers to an intermediate level of noise based on the range summarised in Table 1 and is quoted in the main review citations such as Richardson et al (1995) below.

[129] 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

[130] 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.

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

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

[133] 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

[134] 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.

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

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

[137] 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. Prog. Ser. 309, 279-295

[138] Ingemansson Technology AB (2003) Utgrunden offshore wind farm—measurements of underwater noise. Report 11-00329-03012700. Ingemansson Technology A/S, Gothenburg

[139] 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.

maximum difference in SPL to outside the wind farm of 8 dB re 1 μPa.[140] 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.[141] Noise is also generated by 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.[142] Depending on size, it is likely that tidal current turbines will produce broadband source levels of between 165 and 175 dB re 1μ Pa.[143]

SEISMIC EXPLORATION

Marine seismic surveys are primarily used by the oil and gas industry for exploration, but are also used for other types of research purposes. There are more than 90 seismic vessels available globally,[144] and roughly 20% of them are conducting field operations at any one time.[145]

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 on, amongst other things, the depth of penetration required. These include: air guns, ‘sparkers’, ‘boomers’, ‘pingers’ and ‘chirp sonar’.[146] The main sound-producing elements used in oil exploration are air-gun arrays, which are towed from marine vessels.[147] Air guns release a volume of air under high pressure, creating a sound wave from the expansion and contraction of the released air bubble.[148] 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 also release low amplitude high-frequency sound, and acoustic energy has been measured up to 100 kHz[149]. 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 oil and gas 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.[150] 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

[140] Nedwell, J.R. Parvin, S.J., Edwards, B., Workman, R., Brooker, A.G. and Kynoch, J.2007. Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters. Subacoustech report No. 544R0738 to COWRIE Ltd., Newbury, UK
[141] Wahlberg M, Westerberg H (2005) Hearing in fish and their reactions to sounds from offshore wind farms. Mar Ecol Prog Ser 288:295-309
[142] 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
[143] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[144] Schmidt V (2004) Seismic contractors realign equipment for industry’s needs. Offshore 64:36–44
[145] 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
[146] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[147] Dragoset W (2000) Introduction to air guns and air-gun arrays. Geophys Lead Edge Explor 19:892–897
[148] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[149] Goold, J.C. & Coates, R.F.W. 2006: Near Source, High Frequency Air-Gun Signatures. IWCSC/ 58/E30.
[150] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

surveys conducted more than 3000 km away.[151] Low-frequency energy can also travel long distances through bottom sediments, re-entering the water far from the source.[152]

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[153]. 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.[154]

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.[155]

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.[156] Specialized support ships are used to deploy LFA sonars, which consist of arrays of source elements suspended vertically below the ship. For example, 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 range from 100 to 500 Hz, with a 215 dB re 1 μPa @ 1 m source level for each projector.[157] 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.[158] The signal includes both constant-frequency (CF) and frequency-modulated (FM) components with bandwidths of approximately 30 Hz.[159] A ping sequence can last 6 to 100 seconds, with a time between pings of 6 to 15 minutes 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 operated by the U.S. military, with a proposed expansion to 4 ships in 2011.[160]

[151] 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.
[152] McCauley, R.D., Hughes, J.R. 2006: Marine seismic mitigation measures – perspectives in 2006. IWC SC/58/E44. 10 pp.
[153] CCC/California Coastal Commission 2002: Consistency Determination. No. CD-14-02, USGS,2002 Southern California seismic survey. (In OSPAR 2009)
[154] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[155] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[156] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[157] 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
[158] 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
[159] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[160] 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

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.[161] For example, 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 US Navy system (AN/SQS-56) uses this same frequency band but with lower source levels (223 dB re 1 μPa @ 1m).[162] 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.[163]

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.[164] 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.[165]

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.[166] 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[167] and high intensity seabed mapping (side-scan sonar). Frequencies between 85 and 100 kHz are used for human diver/swimmer detection while 100 kHz is optimal for obtaining a high resolution of seabed features including benthic cover. Hydroacoustic sonars are used to detect the presence of living organisms and particles in oceans, lakes, and rivers.[168] 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.[169]

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).[170] 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.[171] 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 (Figure 2).[172] 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

[161] Watts AJ (2003) Jane's underwater warfare systems, 15th edn. IHS Jane's, Berkshire, UK
[162] 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
[163] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[164] Ibid
[165] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[166] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission
[167] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[168] Simmonds EJ, MacLennan DN (2005) Fisheries acoustics: theory and practice. Blackwell Publishing, London
[169] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[170] Ibid
[171] NRC (National Research Council). 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press. 192pp
[172] OSPAR Commission. (2009). Overview of the impacts of anthropogenic underwater sound in the marine environment. London, UK: OSPAR Commission

shoals of tuna up to 5 km away.[173] Bathymetric mapping sonars use frequencies ranging from 12 kHz for deep-water systems to 70-100 kHz for shallow water mapping systems.[174] Multibeam sonars operate at high source levels (e.g., 245 dB re 1 μPa at 1 m) but have highly directional beams.[175]

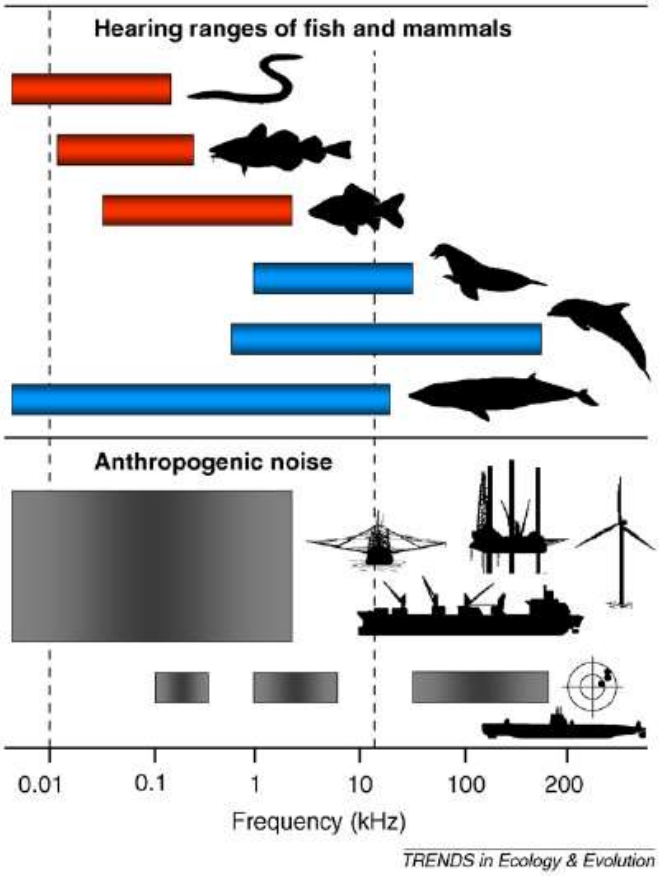

Figure 2. **The main frequencies of anthropogenic noise sources and the hearing ranges of marine mammals and fish (from Slabbekorn et al., 2010)**

SHIPS AND SMALLER VESSELS

Large commercial vessels (length greater than 100m; e.g., container/cargo ships, super-tankers, cruise liners)

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.[176,177,178] The propulsion systems of large commercial ships are a dominant source of radiated underwater noise at frequencies <200 Hz.[179] Individual vessels produce unique acoustic signatures, although these signatures may change with ship speed, vessel load, operational mode and any implemented noise-reduction measures.[180,181]

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[173] Ibid

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

[175] Ibid

[176] 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.

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

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

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

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

[181] 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 made up 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[182]. Smaller, but potentially significant, amounts of radiated noise can arise from on-board machinery (engine room and auxiliary equipment).[183] Hydrodynamic flow over the ship's hull and hull attachments is an important broadband sound-generating mechanism, especially at higher speeds.[184] 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 (where the air/water interface reflects the sound wave and the reflection has an opposite polarity of the original wave).[185] 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.[186,187] Modern cargo ships can also radiate sound at high frequencies, with source levels over 150 dB re 1μPa at 1m around 30 kHz.[188] Vessel noise from a range of different ship types recorded at four locations in Danish waters in 2012 substantially elevated ambient noise levels across the entire recording band from 0.025 to 160 kHz at ranges between 60 and 1000m.[189]

Medium sized vessels (length 50 - 100m; e.g., support and supply ships, many research 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.[190] 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.[191,192] 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 level and frequency to contribute to marine ambient noise in some areas.[193] 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 (length up to 50m; e.g., recreational craft, jet skis, speed boats, operational work boats)

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

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[182] Ibid

[183] 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

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

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

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

[187] 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).

[188] 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.

[189] Ibid

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

[191] 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

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

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

output characteristics can be highly dependent on speed.[194,195,196] 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 in that it does not extend far from the source. Small craft and boats can dominate some coastal acoustic environments, particularly partially-enclosed bays, harbours and/or estuaries.[197] In fact, recreational vessels have been identified as the most important contributor to mid-frequency ambient noise in some coastal habitats.[198] 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).[199] 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.[200] 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 digital devices can either have the same specifications or produce wideband sweeps at broadband source levels of 145 dB 1 μPa.[201]

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.[202,203] 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.[204]

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[194] 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

[195] 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

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

[197] 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

[198] 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

[199] 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.

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

[201] Ibid

[202] 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)

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

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

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)[205]. 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[206] or between 20 and 600 Hz[207]. 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.[208] 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%.[209]

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.[210] The signals could be detected across ocean basins with received levels up to 160 dB re 1 µPa at 1 km distance. 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.[211] 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.[212]

Research projects also use sound to estimate current speed and direction by using drifting sources called SOFAR floats.[213] 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 the distance drifted as a proxy for deep currents.[214]

Icebreakers

Ice-breaking ships are a source of noise in polar regions.[215] Two types of noise have been identified during ice breaking: bubbler system noise and propeller cavitation noise.[216] Some ships are equipped with

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

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

[210] 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.

[211] 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

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[214] 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

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

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.[217]

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 research applications requiring underwater wireless communications.[218]. 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.[219]

[216] 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
[217] Ibid
[218] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[219] 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.

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

Underwater sound is an extremely important component of the marine environment and plays an integral part of the lives of most marine vertebrates[220] and also many invertebrates[221,222]. This chapter provides a synthesis of current scientific knowledge 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 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).[223] Marine animals can be impacted by instantaneous high pressure sound waves, but damage increases with total acoustic energy received for a given type of sound stimulus.[224] Adverse impacts can be broadly divided into three categories: masking, behavioural disturbance and physiological changes (hearing loss, discomfort, injury)[225] although there is some overlap between these categories. In extreme cases, where there are very high levels of received sound pressure 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.[226,227,228,229,230,231,232,233,234,235,236,237] In addition, the

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[220] 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.

[221] 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.

[222] 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

[223] 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.

[224] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

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

[226] 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

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

[228] 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.

[229] 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

[230] 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.

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

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

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

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

[235] 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

[236] Radford, A.N., Kerridge, E. and Simpson, S.D. 2014. Acoustic communication in a noisy world: can fish compete with anthropogenic noise? Behav. Ecol. doi:10.1093/beheco/aru029

potential for more subtle biological effects (e.g., physiological, developmental, cellular and genetic responses) of anthropogenic noise on mainly terrestrial animals has been suggested,[238] which merit investigation in the marine environment.

The chronic and cumulative effects of anthropogenic noise exposure on marine species and populations also require attention.[239] The degree of cumulative effects will also depend on the mobility of marine organisms (and also of the sound source). Highly mobile species may be able to avoid stationary sounds, while more sedentary or sessile species will not be able to move away from a stationary sound source. Migratory species may be subjected to multiple sound sources along their migration route.

This chapter summarizes current scientific knowledge 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 (Figure 3).[240]

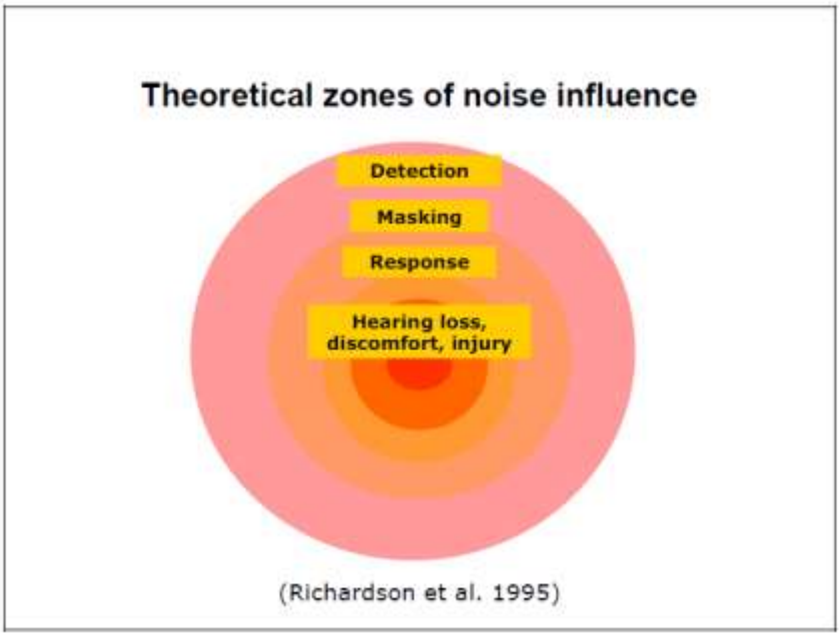

Figure 3. Theoretical zones of noise influence (after Richardson et al. 1995).

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 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

[237] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).
[238] 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
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[240] 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

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[241].

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.[242,243] 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.[244,245,246] 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).[247] 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.[248] 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.[249,250] 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).[251] The mechanism for gas bubble generation (gas bubble disease) in supersaturated tissue of diving marine mammals (that leads to symptoms similar to decompression sickness in humans) is thought to be an adverse behavioural response to exposure to noise[252], or a direct physical effect of sound energy on gas bubble precursors in the animal's body (see Figure 4).[253] 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

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

[242] 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.

[243] 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.

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

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

[247] 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.

[248] Ibid

[249] 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.

[250] 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.

[251] 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.

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

[253] 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

surface, they could experience excessive nitrogen tissue supersaturation driving potentially damaging bubble formation in tissues.[254] However, this is currently a working hypothesis and requires testing through a specific programme of research.[255] 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 and melon-headed whale) showed that there was a stronger response by affected individuals compared to controls for the beaked whales than in the other species.[256] Direct measurements of behavioural responses of Cuvier's beaked whales to mid-frequency active sonar indicate that this species reacts strongly to the acoustic disturbance at low received levels.[257]

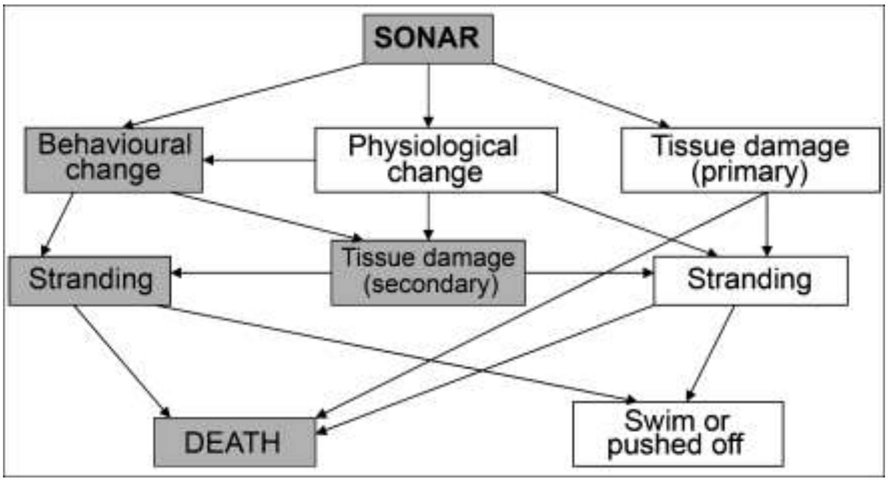

Figure 4. Potential mechanistic pathways by which beaked whales are affected by active sonar. (See Cox et al., 2006 for detailed discussion)

Further mass stranding events of beaked whales and other cetaceans have been reported in a range of locations around the world.[258,259,260] 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 same time and place as naval maneuvres or the use of active sonar or near naval bases.[261] 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, common dolphins and harbour porpoises, have stranded in noise-related events.[262,263,264] The fact that deep diving cetaceans other than beaked whales that have

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

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

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

[257] De Ruiter, S.L. et al. 2013. First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. Biol. Lett. 9: 20130223

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

[259] 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

[260] 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

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

[262] Ibid

[263] Jepson, P.D. et al. 2013. What caused the UK's largest common dolphin (*Delphinus delphis*) mass stranding event? PLoS ONE: e60953.

stranded have been shown to have gas embolism disease suggests that sonar or other noise impacts may be more widespread than previously thought.[265] Additionally, mortality may be underestimated if based solely on stranded individuals, as affected cetaceans are also highly likely to die at sea[266] and not be washed up or detected[267].

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 (e.g., organ damage and rupture of gas filled cavities such as lungs, sinuses and ears) and deaths of marine mammals that have been caused by the use of explosives.[268] A dramatic pressure drop, such as occurs from blast waves, may cause air-filled organs to rupture.[269] The death of two humpback whales was attributed to acoustic trauma caused by a 5000 kg explosion through severe injury to the temporal bones.[270] Underwater detonations as part of military exercises resulted in the death of three (possibly four) long-beaked common dolphins which had sustained typical mammalian blast injuries.[271] There is no documented case of injury caused by pile driving for marine mammals at sea and there remains uncertainty on the effects of pile driving for this taxa[272]. However, experimental studies in captivity using simulated source levels[273,274] 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[275]. Repeated TTS is thought to lead to PTS. Hearing losses can reduce the range for communication, interfere with the ability to forage, increase vulnerability to predators, and may cause erratic behaviour with respect to migration, mating, and stranding.[276] 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 (estimated between 100 and 500 metres for PTS).[277,278] However, using the exposure criteria developed by Southall et al. (2007), a recent study indicates that 50% of tagged harbour seals were predicted to exceed estimated permanent auditory damage thresholds during the construction of an offshore wind farm, even though the seals remained at least 4.7 km from the pile

[264] Southall, B.L., Rowles, T., Gulland, F., Baird, R. W., and Jepson, P.D. 2013. Final report of the Independent Scientific Review Panel investigating potential contributing factors to a 2008 mass stranding of melon-headed whales (*Peponocephala electra*) in Antsohihy, Madagascar

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

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[267] 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

[268] 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

[269] 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

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[271] Danil K, St. Leger JA (2011) Seabird and Dolphin Mortality Associated with Underwater Detonation Exercises. Mar Tech Soc J 45: 89-95

[272] Thompson, P.M., D. Lusseau, T. Barton, D. Simmons, J. Rusin, and H. Bailey. 2010. Assessing the Responses of Coastal Cetaceans to the Construction of Offshore Wind Turbines" Marine Pollution Bulletin 60 (8): 1200-1208

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[274] 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.

[275] 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

[276] Ibid

[277] 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.

[278] 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.

driving source.[279] Previously, the most severe acoustic impacts recorded on cetaceans (active sonar) were due to exposures thought too low to induce TTS, according to predictive models.[280] However, there is considerable variation within the taxa in terms of functional hearing groups,[281] with more recent research on TTS indicating that harbour and finless porpoises are more sensitive to sound than expected from extrapolations based on results from bottlenose dolphins.[282] Hearing damage in marine mammals from shipping noise has not been widely reported and is thought to be unlikely to occur from the passage of a single vessel.[283] However, there is the potential for permanent damage to hearing from sustained and/or repeated exposure to shipping noise over long periods[284]. Increasing collision rates between sperm whales and high-speed ferries in the Canary Islands were thought to be linked to hearing damage. Inner ear analysis of two whales killed in collisions revealed low frequency inner ear damage and auditory nerve degeneration leading to the suggestion that low frequency sounds could be considered a marine hearing hazard.[285]

B MASKING

The term masking refers to what happens when increased levels of background or ambient noise reduces an animal's ability to detect relevant sound[286] such as important acoustic signals for communication and echolocation for marine mammals. If the anthropogenic noise is strong enough relative to the received signal, then the signal will be 'masked'[287]. 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.[288] As ambient noise or transmission range increases, information will be lost at the receiver, ranging from inability to detect subtle features of the signal to complete failure to detect the signal.[289] Consequently, the active space in which animals are able to detect the signal of a conspecific[290] 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 (Figure 5).[291] The principal constituent of low–frequency (5–500 Hz) ambient noise levels in the world's oceans are acoustic emissions from commercial shipping.[292] 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. Concerns regarding the impacts of noise from large vessels have focused mainly on marine animals that use low frequencies for hearing and communication. Vessel noise in higher frequency bands has the potential to interfere (over relatively short

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ranges) with the communication signals of many marine mammals, including toothed whales.[293] Masking of harbour porpoise communication and echolocation at close range (up to 500m) by high-speed ferries and other large vessels has been highlighted as a cause for concern in shallow waters of high traffic coastal areas.[294] 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.[295]

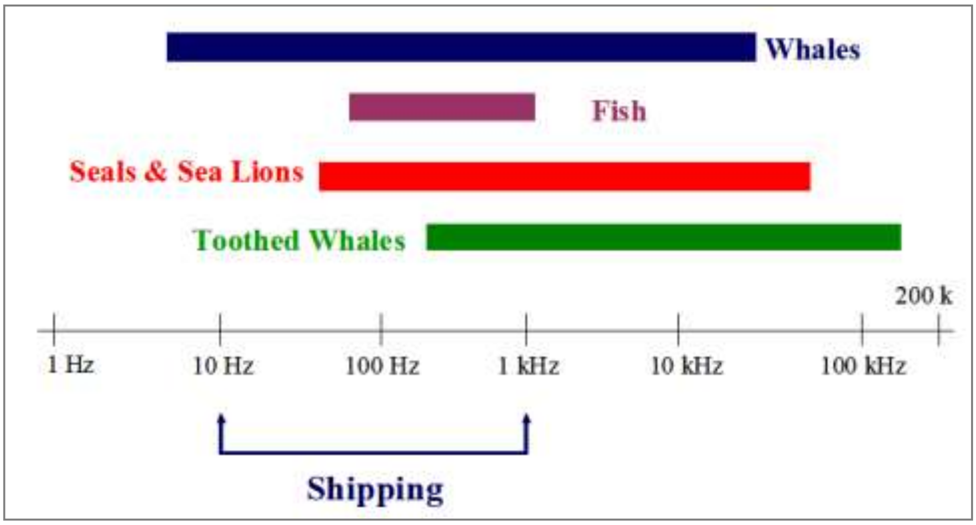

Figure 5. Typical frequency sound bands produced by marine mammals (and fish) compared with the nominal low-frequency sounds associated with commercial shipping (after OSPAR 2009)

There have been numerous studies of the effects of masking from vessel noise on marine mammals, including baleen whales,[296] belugas,[297] bottlenose dolphins,[298,299,300] short-finned pilot whales[301] and killer whales.[302,303] 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.[304,305] For example, the noise of an icebreaker vessel was predicted to mask beluga calls up to 40 km from the vessel[306] while pilot whales in deep water habitat could suffer a 58% reduction in communication range

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caused by the masking effect of small vessels in the coastal zone.[307] Using a metric to measure ‘communication masking’ the acoustic communication space for the highly endangered north Atlantic right whale has shown to be seriously compromised by noise from commercial shipping traffic[308]. 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[309] [310], pile driving sound on bottlenose dolphins[311] and low-frequency wind turbine noise on harbour seals and harbour porpoises[312] [313]. There is also the potential for certain Acoustic Harassment Devices to mask the communication signals of some species of Delphinid cetaceans or seals[314]. 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[315].

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.[316,317,318,319,320,321,322] This phenomenon suggests that the anthropogenic noise levels in the marine environment, such as vessel noise, are clearly interfering with communication in marine mammals.[323] Temporary changes in signalling may enable animals to cope with different noise levels.[324] 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.[325] The energetic and functional costs of making changes to vocalisations for individuals or populations are currently unknown.[326]

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C BEHAVIOURAL CHANGES

A wide range of anthropogenic sound sources are known to elicit changes in behaviour in marine mammals[327,328] (Annex 1) 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.[329,330] Therefore, the extent of behavioural disturbance for any given acoustic signal can vary both within a population as well as within the same individual.[331] Since the first extensive review of marine mammals and anthropogenic noise was completed in the mid-nineties.[332] there have been a number of further detailed appraisals that document how various sources of anthropogenic sound can affect marine mammal behaviour.[333,334,335,336] 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.[337,338] Short term reactions of cetaceans to man-made sounds include sudden dives, fleeing from sound sources, vocal behavioural change, shorter surfacing intervals with increased respiration, attempts to protect their young, increased swim speed and abandonment of the polluted area.[339] For example, both killer whales and dolphins are known to change their motor behaviour in response to small vessel presence and noise,[340,341]

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327 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

328 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

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332 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

333 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

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

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

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337 Ibid (Table 6)

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while baleen whales such as blue and fin whales have similarly responded to shipping movements and noise.[342] Manatees have been shown to respond to approaching vessels by changing fluke rate, heading and dive depth.[343] Cessation of singing was shown in humpback whales with transmissions of an experimental sound 200 km away.[344] 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.[345] However, many types of marine mammals have reacted strongly to the intense sound of seismic surveys. A number of species of baleen whale show avoidance behaviour,[346] as do pinniped species.[347,348] 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.[349] A causal connection between seismic surveys and ice entrapment events leading to narwhal mortality has been proposed recently along with a call for research of the effects of airgun use on narwhals.[350] 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. The observations did, however, show more subtle changes in foraging behaviour at sound levels that were considerably below the threshold level used to predict a disruption of behaviour.[351] These subtle changes were able to be 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.[352] Subtle behavioural responses to ship noise have also been documented for killer whales[353]

It is also important to consider that animals that are most vulnerable to a disturbing stimulus may not be the most responsive, in that the most stressed animals may have less capacity to alter their behaviour.[354] For example, a starving animal may choose to keep feeding when exposed to a disturbing stimulus rather

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than stop feeding and move away.[355] Such trade-offs may influence activity budgets, potentially affecting fecundity, survival[356] and population health[357].

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[358,359] or by reducing energy acquisition in terms of lost feeding opportunities.[360] The displacement of numerous cetacean species has been well documented in the scientific literature[361,362] and, in some cases, individuals have been displaced for a number of years, only returning when the activities causing the anthropogenic noise ceased.[363] 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.[364] 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[365] and dolphins[366]. Vessel noise also influenced the foraging behaviour of Blainville's beaked whale up to at least 5 km away from the source.[367] Noise levels generated by vessels in close proximity may be impairing the ability to forage using echolocation by masking echolocation signals.[368] Sonar-induced disruption of feeding and displacement from high-quality prey patches could have significant and previously undocumented impacts of baleen whale foraging ecology, individual fitness and population health,[369] particularly for endangered species.

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,[370] the life-saving combination of systems and events that maximises the ability of an animal to kill or avoid being killed[371]. 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

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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).[372] 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 and cochlear morphology, the immune system, and DNA integrity and genes.[373] 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. North Atlantic right whales, for instance, showed lower levels of stress-related faecal glucocorticoids after 9-11 due to decreased shipping with an attendant 6 dB decrease in shipping noise.[374]

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[375,376,377] and Southern Resident killer whales[378]). A recent detailed review found little response by cetacean populations to human acoustic disturbance in four case study areas,[379] 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.[380] Indeed, behavioural change should not necessarily be correlated with biological significance when assessing the conservation and management needs of species of interest.[381] A study that modelled coastal bottlenose dolphins to assess the effect of increased levels of vessel traffic on behaviour suggested that the dolphins' response to disturbance is not biologically significant, as they were able to compensate for the change in behaviour so that their health was unaffected.[382] This modelling scenario was based on the condition that increased commercial vessel traffic was the only escalation in anthropogenic activity affecting the dolphin population.

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).[383] The model, developed for marine mammals but theoretically applicable to other fauna,

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[380] 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.

[381] New, L.F et al. 2013. Modelling the biological significance of behavioural change in coastal bottlenose dolphins in response to disturbance. Functional Ecology 27: 314-322.

[382] Ibid

[383] 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.

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 gaps, including those related to uncertainties in population estimates for species or regions, difficulties in weighting noise against other stressors and the inherent inaccessibility of the marine environment.[384] No one factor is likely to be harmful enough to cause a direct population decline, but a combination of factors may create the required conditions for reduced productivity and survival in some cases.[385]

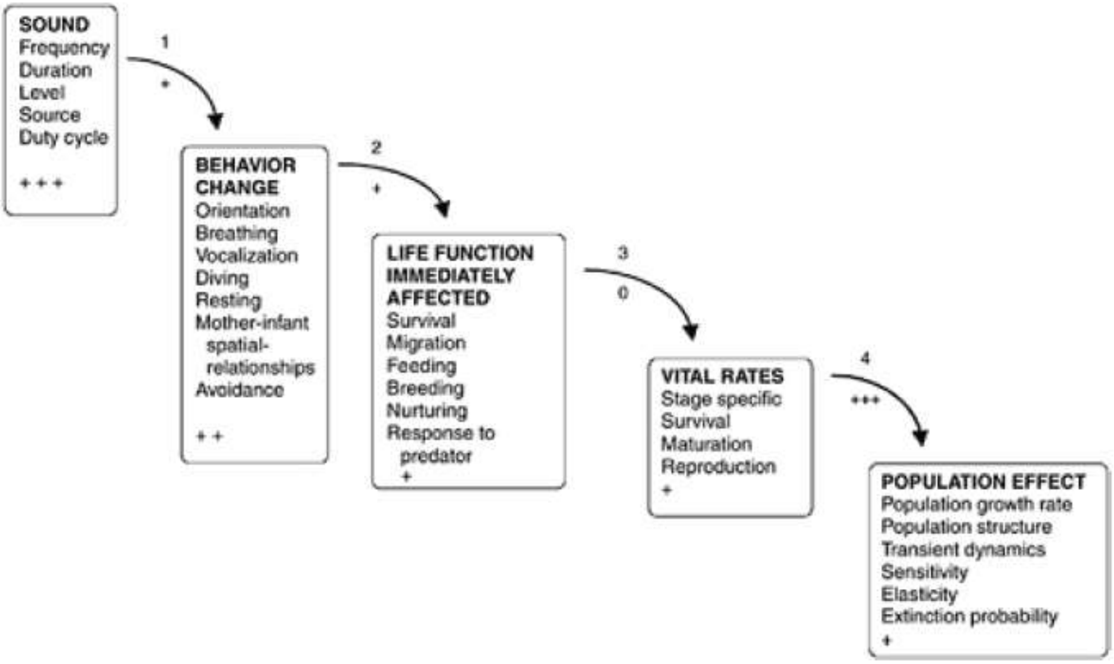

Figure 6. Overview of the PCAD Model by NRC (2005)

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.[386, 387] These various stressors may also act synergistically or cumulatively. For example, underwater noise could interact with bycatch or ship strikes in that the individual is less able to detect the presence of fishing nets or nearby vessels.[388] Multiple sources of anthropogenic sound may also interact cumulatively or synergistically such as when naval sonar emissions from multiple vessels produce confusing sound fields.[389]

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

[385] 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.

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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.[390,391] Also, much of the material available is in the form of technical reports or 'grey literature'.[392] An evaluation of both the peer-reviewed and grey literature in 2009 concluded that very little is known about the effects of anthropogenic sound on fish and that there is a need for a systematic programme of study on a range of species.[393] Since then, the number of peer-reviewed publications has increased considerably, but there are still large gaps in our knowledge of the effects of underwater noise on fish.[394]

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.[395] The impacts of intense sound over short periods have been studied in some detail with respect to physical trauma and behaviour,[396,397 398,399] but there is currently very little data available for the effects of ambient noise on fish behaviour[400]. Where data are lacking, inferences can be drawn by assessing noise-related impacts on the behaviour of other vertebrates.[401] 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.[402] 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.[403] A significant hearing threshold shift was reported for rainbow trout exposed to a playback of low-frequency

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

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

[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] 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

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[400] 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.

[401] Ibid

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

[403] Ibid

active (LFA) sonar at an SPL of 193 dB re 1 µPa.[404] More recent studies found no TTS in rainbow trout exposed to mid frequency active (MFA) sonar at an SEL_{cum} of 220 dB re 1 µPa^2 s[405] but TTS in channel catfish both for MFA[406] and LFA sonar.[407] However, in both studies conducted on channel catfish, not all of the individuals tested showed a temporary loss of hearing . No loss of hearing was also reported for largemouth bass and yellow perch in the same experimental conditions.[408] Channel catfish have morphological adaptations that increase pressure sensitivity, while the other species analysed in these two studies do not. In addition, the variation of effects on the auditory system suggests that susceptibility to intense sound is more a function of genetic stock, developmental conditions, seasonal variation and the state of the animal during exposure than interspecific differences.[409]

A field-based study of hearing loss in four coral reef fish species during a seismic survey did not find any loss of hearing up to 193 dB re 1 µPa.[410] Hearing impairment, namely 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.[411,412] 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.[413] 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 some studies,[414,415,416,417] but no damage was reported in some others[418,419]. 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.[420] Furthermore, the hair cell damage recorded in these studies was only a visual manifestation of what may have been a much greater effect.[421] Damage to the lateral line organ in fish has

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404 Popper, A. N., Halvorsen, M. B., Kane, E. et al. (2007). The effects of high-intensity, low-frequency active sonar on rainbow trout. Journal of the Acoustical Society of America 122, 623–635

405 Halvorsen, M.B. et al. 2012. Effects of mid-frequency active sonar on hearing in fish. J. Acoust. Soc .Am. 131: 599-607

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408 Ibid

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410 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).

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412 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.

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419 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.

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

also been proposed when individuals are in close proximity to an intense sound source [422] and the suggested mechanism for this is the decoupling of the cupulae from the neuromasts[423].

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.[424] Ruptured swim bladders have been reported in fish exposed to explosions[425,426,427] and to pile driving sound in some studies[428,429,430,431,432]but no damage was reported in some others[433]. The threshold for the onset of injury from pile driving sound in juvenile Chinook salmon was recently defined as an SEL_{cum} of 210 dB re 1 μPa^2 s[434]. 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.[435] Fish that do not possess swim bladders such as flatfish are less susceptible to damage from explosions.[436] 'Blast fishing' explosions on tropical coral reefs not only kill and injure fish and invertebrates but cause extensive damage to reef habitat.[437] Blasts occurring during the decommissioning of oil and gas platforms can also cause in fish mortality.[438] It has been suggested that fish may be susceptible to two types of tissue damage when exposed to intense sound.[439] Firstly, sufficiently high sound levels are known to cause the formation of micro-bubbles in the blood and fat tissue.[440] Growth of these bubbles by rectified diffusion[441] at low frequencies could create an embolism and either burst small capillaries, causing superficial or internal

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423 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.

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430 Caspar et al., 2012. Recovery of barotrauma injuries in Chinook Salmon, *Oncorhynchus tshawytscha* from exposure to pile driving sound. PLoS ONE: e9593

431 Halvorsen et al. 2012. Threshold for onset of injury in chinook salmon from exposure to impulsive pile driving sounds. PLoS ONE: e38968

432 Caspar et al. 2013. Recovery of barotrauma injuries resulting from exposure to pile driving sound in two sizes of hybrid striped bass. PLoS ONE: e73844

433 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.

434 Halvorsen et al. 2012. Threshold for onset of injury in chinook salmon from exposure to impulsive pile driving sounds. PLoS ONE: e38968

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

436 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.

437 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.

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

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441 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.

bleeding, or cause damage to fish eyes where tissue may have high gas saturation.[442] 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.[443]

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.[444,445] Turbot larvae also suffered damage to brain cells and to neuromasts of the lateral line.[446] The neuromasts are thought to play an important role in escape reactions for many fish larvae, and thus their ability to avoid predators.[447] 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 are most vulnerable.[448] Juveniles and fry have less inertial resistance to the motion of a passing sound wave, and are potentially more at risk for non-auditory tissue damage than adult fish.[449]

A recent study that exposed larvae of the common sole to high levels of pile-driving sound in carefully controlled experimental conditions did not record any significant differences in larval mortality between exposure and control groups.[450] The highest cumulative sound exposure level used was 206 dB re 1μPa^2 s, which is more than the interim criteria for non-auditory tissue damage in fish.[451] Juvenile European sea bass exposed 'in situ' to pile driving sounds resulting in a cumulative sound exposure of between 215 and 222 dB re 1μPa^2 s did not differ in immediate mortality compared to controls.[452] There were also no differences in delayed mortality up to 14 days after exposure.

The very limited data available for the effects of sonar on fish show no evidence of tissue damage or mortality to adult fish.[453] Studies focused on larval and juvenile fish exposed to mid-frequency sonar recorded significant mortality (20-30%) of juvenile herring in 2 out of 42 experiments,[454] 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.[455] However, there is a need to repeat these experiments, as the sound level was

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

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[448] 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

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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.[456]

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.[457] Fish behaviour is also often observed in a cage or tank, which can provide some useful information regarding the initial response to a sound,[458] but is not representative of behaviour when exposed to the same sound in the wild, for example in a spawning or feeding ground[459]. 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.[460] 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.[461,462] 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.[463]

An alarm or escape reaction, can be triggered when fish receive a strong sound stimulus;[464,465] such as an air-gun array[466]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[467].

Avoidance behaviour of vessels, vertically or horizontally in the water column, has been reported for cod and herring, and was attributed to vessel noise.[468],[469] Vessel activity can also alter schooling behaviour and swimming speed of fish.[470] A recent review of fish avoidance of research vessels indicates that simple behavioural models based on sound pressure levels are insufficient to explain how fish react to survey vessels, and that research is needed into the stimuli that fish perceive from approaching vessels, particularly low-frequency infrasound.[471]

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

[457] Ibid

[458] 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.

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

[460] Ibid

[461] Ibid

[462] 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.

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

[470] 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.

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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.[472] Schools of wild pelagic fish (sprats and mackerel) in a quiet coastal location mainly responded to simulated pile driving sound by dispersing and changing depth respectively.[473] There has been concern regarding the effect of impulsive sound on migratory fish where pile driving was conducted in a narrow straight used by salmon during the migration season.[474] The recorded sound levels (190 dB 1 µPa s at 28 m from the pile) were deemed high enough to block migration and potentially cause hearing damage to fish passing close to the pile. Modelling of pile driving effects on migrating European sea bass using experimental behavioural data predicted that fish would take significantly longer to arrive at their spawning site which could have important implications at a population level.[475] The temporal structure of sound can also affect behaviour. Sea bass exposed to both intermittent and continuous sound showed significantly slower recovery from the former compared to the latter.[476] It was suggested that intermittent sound (e.g., pile driving) may have stronger behavioural impacts on some fish than continuous sounds (e.g., drilling) although further research is required to verify this for other species.

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.[477,478] Similarly, a 52% decrease in rockfish catch (hook-and-line fishery) was reported when the catch area was exposed to a single air-gun array[479] which may have been caused by a change in swimming depth or shoaling behaviour.[480] Conversely, gillnet catches of redfish and Greenland halibut doubled during seismic shooting, although longline catches of haddock and Greenland halibut dropped, compared to pre-shooting levels[481]. 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.[482] 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.[483] Schools of herring did not react to a full-scale 3D seismic survey, which was attributed to a strong motivation for feeding, a lack of suddenness of the air gun stimulus (use of ramp up procedures) and an increased level of tolerance to the seismic survey.[484] Mid-

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frequency active sonar did not elicit a significant behavioural response in herring in terms of vertical or horizontal escape reactions.[485] Similarly, herring did not react significantly to low-frequency sonar signals from a passing vessel but did show a reaction to the sound of a two stroke engine at a much lower SPL.[486] 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.[487] 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).[488]

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[489]. 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. A similar study involving the same species and the European minnow found that both species foraged less efficiently but their foraging behaviour was altered in different ways, with the minnow feeding less often whilst the stickleback fed at the normal rate but made more mistakes[490]. A significant modification in foraging habits has also been reported for Mediterranean damselfish due to recreational boat noise[491]

Increased levels of anthropogenic noise in the marine environment may also invoke a stress response in fish. 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.[492] Studies of captive freshwater fish exposed to simulated boat noise for 30 minutes found increased level of the stress hormone cortisol in the blood.[493] Noise-related increases in heart rate, muscle metabolism and metabolic rates have also been reported for captive fish.[494,495,496] Analysis of biochemical and haematological parameters, stress indexes and growth rate for farmed fish exposed to different types of background noise showed that fish exposed to noise from onshore facilities were more stressed than those exposed to background noise from offshore aquaculture.[497] Although data are lacking for wild fish in terms of noise-related stress effects, these

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studies at least suggest that anthropogenic noise could be a stressor in natural water bodies.[498] 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 so.[499,500] 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,[501,502] 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.[503] Fish are known to produce sounds during territorial fighting, when competing for food or when being attacked by a predator.[504] Acoustic communication can also be extremely important for courtship interactions[505] and in spawning aggregations.[506] There is evidence that acoustic communication can affect the survival and reproductive success of fish.[507,508] 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.[509,510] 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.[511] 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,[512] while sexual signals for mate selection in frogs[513] have been masked in

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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. The noise of large ferries has been shown to mask the sound of Atlantic croaker calls, restricting communication.[514]

Changes in fish acoustic behaviour in noisy environments have been found in a few cases. The mean pulse rate of sounds produced by brown meagres (*Sciaena umbra*) increased following repeated boat passes compared to ambient conditions, which was assumed to be caused by boat noise.[515] However it was not known whether the increase in vocal activity was caused by an increased density of callers or by an increased acoustic output by those individuals already calling. More recently, clear evidence for the Lombard effect in fishes has been reported for a freshwater fish, the Blacktail Shiner (*Cyprinella venusta*).[516] This species increased its call amplitude in the presence of elevated background noise levels in experimental conditions by increasing the spectral levels of acoustic signals. The capacity of fish to exhibit the Lombard effect is thought to be constrained by body size and the energetic costs of producing louder sounds.[517] Changes in call frequencies in response to abiotic noise sources[518] or to tidal state[519] have been also been reported in fish but only for individual species. Further research is required in both laboratory and field conditions to determine whether the Lombard effect and other changes in vocal behaviour (see Radford et al., 2014 for potential ways) occur for many other fish species.

Anthropogenic noise may also interfere with prey or predator detection in marine fish.[520] 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.[521] 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 hydrodynamic noise generated by approaching predators.[522,523] 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.[524] 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.[525]

Antipredator behaviour has recently been shown to compromised by anthropogenic noise in some fish species for laboratory-based studies, but not for others. In playback experiments juvenile European eels were significantly less likely to be startled by an ‘ambush predator’ and caught more than twice as

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quickly by a ‘pursuit predator’.[526] It was suggested that acoustic disturbance could have important physiological and behavioural impacts on animals, compromising life-or-death responses. Antipredator behaviour in two species of sympatric fish was not shown to be compromised when exposed to additional noise, with one species having a faster antipredatory response, which could be caused by increased vigilance.[527]

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.[528,529,530] Fish larvae have also been shown to return to their natal reef,[531,532] 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[533] that are used by some species of juvenile reef fish for nocturnal orientation.[534] 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.[535] It has been suggested that increased levels of noise may inhibit orientation and/or settlement of fish larvae on coral reefs by masking the necessary acoustic cues received by larval fish.[536] Indeed, orientation of cardinalfish larvae was affected by boat noise in a choice chamber experiment, with significant directional responses recorded for reef+boat playback compared to reef only.[537] 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 further verification. Shipping noise from engines has also been shown to attract settlement of mussel larvae, causing biofouling of ship hulls.[538]

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.[539]

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).[540]

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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.[541] 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.[542]

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.[543] Elasmobranchs do not appear to be as sensitive to sound as teleost fish when measured in comparable ways.[544] 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.[545]

Anthropogenic noise sources that have the potential to affect elasmobranchs are thought to be pile driving, wind turbines and boat noise.[546] Elasmobranchs have been reported to aggregate around coastal and offshore man-made structures.[547] 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.[548] Secondly the impact of the hammer on the pile may cause barotrauma in elasmobranchs, which has recently been reported in some organs in teleost fish including the liver and kidneys.[549] Demersal elasmobranchs such as skates and rays may also be damaged by the intense vibrations in the sediments that are caused by pile driving.[550] 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).[551] 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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[551] Ibid

IMPACTS ON OTHER MARINE ORGANISMS

Other marine animals that are sensitive to underwater sound include marine turtles,[552] and many invertebrates.[553,554] 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 100 to 400 Hz.[555,556] Juvenile green turtles are sensitive to a broader and higher frequency range of 50 – 1600 Hz.[557] 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.[558] Most experimental studies to assess short-term responses have demonstrated a strong initial avoidance response in marine turtles to air-gun arrays[559,560,561] 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.[562] 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.[563] A recent monitoring assessment recorded that 51% of loggerhead turtles dived at or before their closest point of approach to the air-gun array.[564] Conversely, olive ridley turtles did not react to air gun shots.[565] No significant changes in behaviour were recorded for diamondback terrapins exposed to playback recordings of approaching boat engines.[566]

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.[567] Avoidance behaviour may result in significant changes in turtle distribution with potential consequences for individuals or populations if displaced from

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[552] 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

[553] 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

[554] 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.

[555] 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

[556] Lavendar, A.L., Bartol, S.M. and Bartol, I.K. 2014. Ontogenetic investigation of underwater hearing capabilities in loggerhead sea turtles (*Caretta caretta*) using a dual testing approach. The Journal of Experimental Biology 217: 2580-2589.

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[558] 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

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

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

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

[562] Ibid

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

[564] DeRuiter, S.L. and Doukara, R.L 2012. Loggerhead turtles dive in response to airgun sound exposure. Endangered Species Research, 16, 55–63

[565] Weir, C.R. 2007. Observations of marine turtles in relation to seismic airgun sound off Angola. Marine Turtle Newsletter, 116, 17−20.

[566] Lester LA, Avery HW, Harrison AS, Standora EA .2013. Recreational Boats and Turtles: Behavioral Mismatches Result in High Rates of Injury. PLoS ONE 8(12): e82370.

[567] 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

their preferred feeding habitat.[568] 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.

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[569] but able to detect up to 3 kHz in some species[570]. Cephalopods are sensitive to water movement stimuli in a range between <20 and 1500 Hz.[571,572]. 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.[573,574,575,576] In some species of invertebrates the sounds emitted are thought to be ecologically important in terms of acoustic communication between conspecifics.[577] It has been suggested that acoustic communication and perception in invertebrates might be related to as many functions as in marine vertebrates.[578]

At the time of writing there are no reported research studies to determine the effects of a number of anthropogenic noise sources (e.g., 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,[579] 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. These sources have been investigated to some extent in terms of physical and behavioural reactions, and recently for stress responses and effects on larvae for a few marine species.

Initial studies 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,[580] 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.

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

569 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

570 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.

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

572 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.

573 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.

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

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

576 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

577 Ibid

578 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

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

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

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.[581]

There are however a number of more recent studies that should be mentioned for airgun effects. Firstly a significant increase in the strandings of giant squid in Spain during 2001 and 2003 coincided with the proximity of seismic survey vessels conducting air-gun arrays.[582] 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.[583] 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.[584] Lesions in the sensory and lining epithelia of the statocysts, and damaged sensory hair cells and nerve fibres were reported in each species.[585] In particular, massive lesions were found in cuttlefish for all noise exposed individuals.[586] The number of lesions also increased with greater exposure to low frequency sound, Regeneration of statocyst sensory epithelium was also tentatively identified but requires further study for verification. As relatively low levels of low-frequency sound and short exposure had induced severe acoustic trauma in these cephalopods, it was suggested that there may be considerable effects of similar noise sources on these species in natural conditions over longer time periods.[587]

[581] McCauley RD, Duncan AJ, Penrose JD, et al. 2000. Marine seismic surveys – a study of environmental implications. APPEA J 40: 692–706.
[582] 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.
[583] 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)
[584] Andre et al., 2011. Low-frequency sounds induce acoustic trauma in cephalopods. Front Ecol Environ 9: 489–493,
[585] Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., van der Schaar, M., André, M. 2013. Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? Deep Sea Research Part II: Topical Studies in Oceanography. doi:10.1016/j.dsr2.2012.10.006
[586] Ibid
[587] Andre et al., 2011. Low-frequency sounds induce acoustic trauma in cephalopods. Front Ecol Environ 9: 489–493

Noise effects on marine invertebrate larvae have recently been demonstrated for a number of types of low frequency sound. Almost half (46%) of scallop larvae (*Pecten novaezelandiae*) exposed to playbacks of seismic pulses developed body abnormalities and significant developmental delays were also evident.[588] Playbacks of boat noise to sea hare embryos (*Stylocheilus striatus*) also delayed development, and increased mortality of recently hatched larvae.[589] In laboratory experiments, exposure to continuous sound from tidal or offshore wind turbines significantly delayed megalopae metamorphosis in two species of brachyuran crab when compared to development in natural habitat sound[590].

A number of behavioural responses to anthropogenic noise have been reported in recent publications for marine invertebrates. Foraging and antipredator behaviour of shore crabs (*Carcinus maenas*) was negatively affected by playback of ship noise in controlled tank-based experiments suggesting an increased risk of starvation or predation.[591] Ship noise also increased the settlement rate of green-lipped mussel larvae (*Perna canaliculus*),[592] which may have connotations for ship fouling by mussels. A study of noise-related effects on cuttlefish behaviour indicates that interference of the acoustic sensory channel affected signalling in another (visual) sensory channel—i.e. anthropogenic noise has a marked effect on the behaviour of a species that does not rely on acoustic communication.[593] All sensory channels should therefore be considered when trying to understand the overall effects of anthropogenic stressors such as noise on animal behaviour.

More subtle physiological changes could also occur in an environment exposed to noise. For example, brown shrimp exposed to increased background noise for up to three months demonstrated significant decreases in both growth and reproductive rates.[594] Shrimps were also more aggressive in the noisy treatments with increased mortality and decreased food intake. These are often regarded as symptoms of stress in vertebrates. Stress responses to playbacks of shipping noise have been reported for a number of marine crustaceans. Components of the haemato-immunological system of the Mediterranean spiny lobster (*Panulirus elephas*) were altered[595] while the metabolic rate of the shore crab (*Carcinus maenas*) increased for crabs experiencing ship-noise playbacks compared to ambient noise.[596] Exposing red swamp crayfish (*Procambarus clarkii*) to low frequency sound also produced significant variations in haemato-immunological parameters.[597]

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[598] or the detection of prey or predators by cuttlefish[599].Masking of important acoustic

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[588] Aguilar de Soto, N., Delorme, N., Atkins, J., Howard, S., Williams, J. and Johnson, M. 2013. Anthropogenic noise causes body malformations and delays development in marine larvae. Scientific Reports, 3: 2831

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[590] Pine MK, Jeffs AG, Radford CA .2012. Turbine Sound May Influence the Metamorphosis Behaviour of Estuarine Crab Megalopae. PLoS ONE 7(12): e51790

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[593] Kunc, H.P., Lyons, G.N., Sigwart, J.D. et al. 2014. Anthropogenic noise affects behavoir across sensory modalities. American Naturalist 184: E93-E100

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

[595] Filiciotto, F., Vazzana, M, Celi, M., et al. 2014. Behavioural and biochemical stress responses of *Palinurus elephas* after exposure to boat noise pollution in tank. Marine Pollution Bulletin 84: 104-114

[596] Wale MA, Simpson SD, Radford AN. 2013 Size-dependent physiological responses of shore crabs to single and repeated playback of ship noise. Biol Lett 9: 20121194.

[597] Celi, M., Filiciotto, F., Parrinello, D. et al., 2013. Physiological and agonistic behavioural response of *Procambarus clarkii* to an acoustic stimulus. J. Exp. Biol. 216, 709–718.

[598] 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

[599] Kunc, H.P., Lyons, G.N., Sigwart, J.D. et al. 2014. Anthropogenic noise affects behavoir across sensory modalities. American Naturalist 184: E93-E100

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 reduces successful recruitment.[600]

SEABIRDS

More than 800 species of birds live on or near water, many of whom dive when foraging for food,[601] including cormorants, grebes, auks, murres and sea ducks, not to mention penguins. Diving seabirds can be exposed to underwater noise when feeding but there are no reported studies of the effects of noise on the hearing of seabirds.[602,603] Noise-induced damaged to hair cells has been measured in terrestrial birds although as a group, birds are considered more resilient to auditory damage than mammals as they can replace hair cells of the cochlea and vestibular system.[604] Severe non-auditory damage of seabirds exposed to intense noise in the form of explosions has been reported for western grebes following an underwater detonation from military training activities.[605] Birds attracted to fish kills after initial detonations were subsequently impacted by further blasts leading to 70 individuals washed up on a nearby beach. Necropsy of 10 birds confirmed that the blast injuries were sustained by the grebes were the cause of death. Diving seabirds are likely to be at greater risk of a noise impact if they are attracted to feed on dead or disorientated fish in the vicinity of impulsive sources such as seismic arrays, pile driving or explosives.[606]

There are very few studies of diving birds reacting to underwater noise. Underwater playback of chase-boat engines has successfully been used to scare diving birds and reduce predation of farmed mussels by eider ducks, long-tailed ducks and common scoters.[607,608] Playbacks of underwater noise were also used to scare African penguins out of an area where blasting was planned.[609] However no specific and detailed behavioural studies of the noise effects on seabirds have been conducted to date. Strong behavioural reactions to sudden or loud airborne sounds have been documented for seabirds such as king penguins[610] and crested terns[611]. However, it is not known whether seabirds are as sensitive to underwater noise as to airborne sound,[612] although it has been suggested that diving birds may not hear well underwater and that

[600] 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

[601] Dooling, R.J. and Therrien, S.C. 2012. Hearing in Birds: What changes from air to water. In A.N. Popper and A. Hawkins (eds.), The Effects of Noise on Aquatic Life. Pp. 77-82. Advances in Experimental Medicine and Biology 730, DOI 10.1007/978-1-4419-7311-5_17

[602] Ibid

[603] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

[604] Dooling, R.J. and Blumenrath, S.H. 2013. Avian sound perception in noise. In H. Brumm, ed. Animal Communication and Noise. pp. 229-250. Springer, Berlin Heidelberg. http://link.springer.com/chapter/10.1007/978-3-642-41494-7_8.

[605] Danil, K. and St. Leger, J.A. 2011. Seabird and dolphin mortality associated with underwater detonation exercises. Marine Technology Society Journal, 45(6), 89-95.

[606] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

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[609] Cooper J. 1982. Methods of reducing mortality of seabirds caused by underwater blasting. Marine Ornithology 10, 109-113.

[610] Wilson, R. P., Culik, B., Danfeld, R., and Adelung, D. 1991. People in Antarctica, how much do adelie penguins, Pygoscelis adeliae, care? Polar Biology, 11:363-370.

[611] Brown, A. 1990. Measuring the effect of aircraft noise on lated jet aircraft noise on heart rate and behaviour of sea birds. Environment International, 16, 587-592

[612] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

the frequency of best hearing is lower (2 -4 kHz.) in water than in air[613]. If diving seabirds and penguins are vulnerable to underwater noise, a behavioural change could lead to reduced foraging or avoidance of a feeding area with possible implications for survival and fitness. This is especially applicable to penguins as they spend long periods in the water foraging and diving.[614]

The lack of information available for diving seabirds hearing in water and whether there are significant effects of underwater noise strongly supports the need for a detailed programme of research. Comparative anatomical studies of diving birds middle and inner ears are required along with behavioural studies of hearing in air and in water.[615] Secondly, behavioural studies of these birds in their natural habitats are needed to determine whether sound is used to communication, foraging, predator avoidance or other behaviour.[616]

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[613] Dooling, R.J. and Therrien, S.C. 2012. Hearing in Birds: What changes from air to water. In A.N. Popper and A. Hawkins (eds.), The Effects of Noise on Aquatic Life. Pp. 77-82. Advances in Experimental Medicine and Biology 730, DOI 10.1007/978-1-4419-7311-5_17

[614] Aguilar de Soto, N. 2015. Physiological effects of noise on aquatic animals. . In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

[615] Dooling, R.J. and Therrien, S.C. 2012. Hearing in Birds: What changes from air to water. In A.N. Popper and A. Hawkins (eds.), The Effects of Noise on Aquatic Life. Pp. 77-82. Advances in Experimental Medicine and Biology 730, DOI 10.1007/978-1-4419-7311-5_17.

[616] Ibid.

5. FUTURE RESEARCH NEEDS

This assessment of anthropogenic noise and its effect 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.[617] 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 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. 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 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,[618,619,620] and also specific research needs for other taxa[621,622] 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 of mitigation procedures and measures

Research needs for mitigation procedures and measures are not discussed in this document.

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[617] 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.

[618] MMC (Marine Mammal Commission) 2007. Marine mammals and noise: a sound approach to research and management. Marine Mammal Commission, Bethesda, Maryland. 370pp.

[619] 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.

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

[622] 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

In addition to the previously mentioned reviews of research needs, a recent gap analysis[623] has identified a number of key areas in need of research areas:

- Describing Soundscapes
- Impacts of Particular Sound Sources
- Effects of man-made sounds on marine animals
- Mitigation of effects
- Measurement and decryption of sounds and the conduct of acoustic experiments

Key research needs and developments recommended by this gap analysis are also incorporated into Table 5, with the exception of mitigation of effects.

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.[624] 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.[625] Anthropogenic noise sources are also often distributed heterogeneously in time and space which contributes to the complexity of underwater 'soundscapes' that marine organisms inhabit.[626] 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.[627] 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.

[623] Hawkins, A.D., Pembroke, A.E. and Popper, A.N. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fisheries. 25: 39-64
[624] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[625] Ibid
[626] 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
[627] Ibid

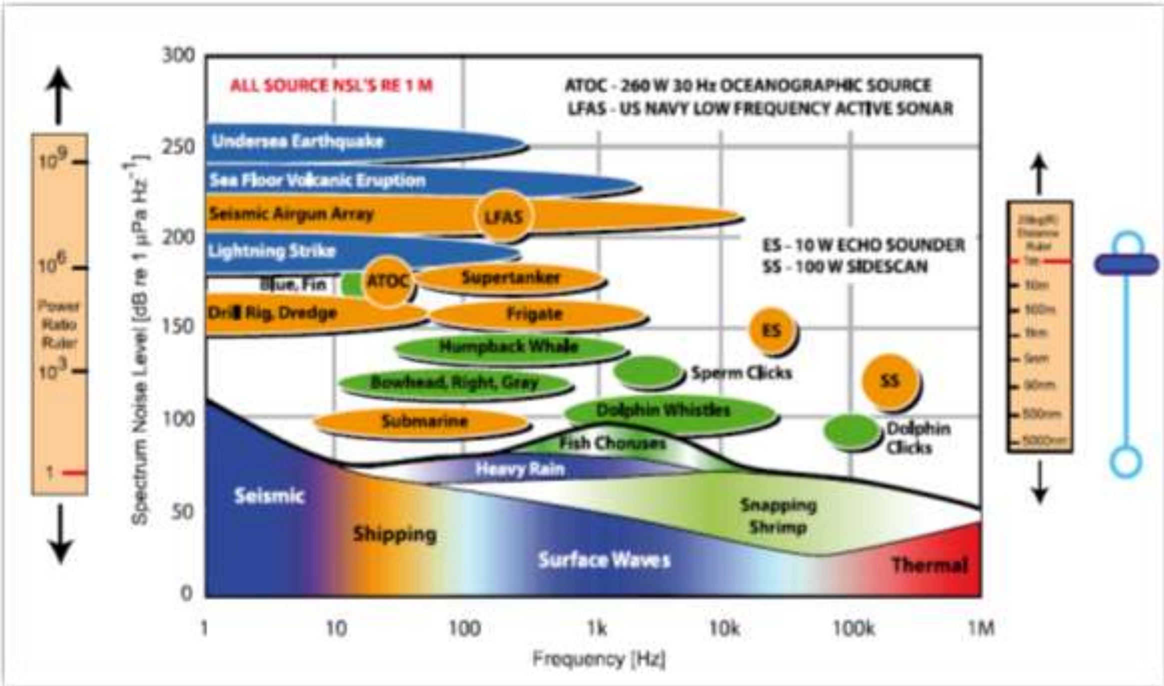

Figure 7. **Noise levels and frequencies of anthropogenic and naturally occurring sound sources in the marine environment (Seiche graphic)**

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 natural 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 surveys, pile driving, as well as oil drilling and production.[628] 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.[629] 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.[630]

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.[631] Establishing sound monitoring stations and

[628] 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.
[629] Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser 395:4-20
[630] Ibid.
[631] Ibid

programmes to survey different types of underwater soundscapes are required to build up a greater understanding of the underwater acoustic environment and how this is changing. A long-term aim should be the development of underwater anthropogenic acoustic thresholds for marine ecosystems to determine the amount of anthropogenic sound an ecosystem can tolerate without its status being altered.[632]

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)[633,634] and the mechanism for this chemical relaxation-based acoustic energy loss is well known.[635] More than 50% reduction in the absorption of sound at 200 Hz has been predicted in high latitudes (e.g., North Atlantic) by 2100[636] although these predictions have recently been disputed by subsequent modelling studies.[637] 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 considerably more biological and ecological information for a particular species is available. Information for species and populations is incomplete for many marine animals, particularly for 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 there is a lack of basic biological information for many threatened species that is relevant to underwater acoustics. For example elasmobranch fish are recognised as highly threatened taxa[638] but very little is known about their sense of hearing with data available for only a few species[639]. 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[640] species as surrogates for less-common or more-difficult-to-test species[641] or on a wide range of morphologically and taxonomically diverse species of interest[642]. 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

[632] Hawkins, A.D., Pembroke, A.E. and Popper, A.N. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fisheries. 25: 39-64

[633] 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

[634] 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

[635] 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.

[636] 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

[637] 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

[638] Godin AC, Worm B (2010) Keeping the lead: How to strengthen shark conservation and management policies in Canada. Mar Policy 34:995-1001

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

[640] those thought to adequately represent related species on which such data are not available

[641] 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.

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

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[643] 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. Again, prioritisation of marine species for research will be required and the same criteria mentioned previously for selection should apply. Key research areas are listed in Table 5 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 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[644] and only a few studies have observed noise impacts on fish in their natural environment[645]. For non-behavioural research new technology may need to be developed to monitor particular noise effects *'in situ'* via devices such as smart' tags e.g., for measurements of hearing loss, metabolism and the production of stress hormones.

The chronic and also cumulative effects of anthropogenic noise on marine organisms and populations have received some attention in recent years, particularly for marine mammals[646] [647], 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[648] 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.[649]

[643] 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.

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

[645] 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.

[646] 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.

[647] 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

[648] Bejder L (2005) Linking short and long-term effects of nature-based tourism on cetaceans. PhD dissertation, Dalhousie University, Halifax, NS

[649] 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

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,[650] 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.[651] Masking of important orientation cues may also occur for both fish and invertebrate larvae prior to settlement.[652,653] 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.

Thus far, the socio-economic consequences of noise-induced impacts on marine populations have not been substantially considered by the research community although the subject is receiving attention in some regions.[654] Avoidance of noisy areas or reduced population success may 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.[656,657,658,659] Early experimental work in the sea confirmed the importance of working under appropriate acoustic conditions.[660] For laboratory-based work investigating anthropogenic sound effects on marine taxa, it is extremely important that the experimental acoustic conditions accurately depict either natural conditions found in the sea or the sound properties of anthropogenic sources. For example, considerable research has been carried out in small tanks where the acoustic field is considerably different to that found in the natural environment.[661] The tanks themselves can alter the acoustic field in certain conditions making the determination of meaningful results difficult. Care must also be taken when comparing different types of audiograms used to estimate hearing

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650 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

651 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

652 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.

653 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

654 European Commission 2013. Marine Strategy Framework Directive (MSFD) Common Implementation Strategy (CIS). 82 pp. (see Technical Group for Underwater Noise – p. 45): http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/implementation/pdf/MSFD%20CIS%20future%20work%20programme%202014.pdf.

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 Hawkins, A.D., Pembroke, A.E. and Popper, A.N. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Rev. Fish. Biol. Fisheries. 25: 39-64

660 Hawkins A D. 2014. Examining Fish in the Sea: A European Perspective on Fish Hearing Experiments. In: Perspectives on Auditory Research. Springer, pp 247-267

661 Rogers PH, Hawkins AD, Popper AN, Fay RR, Gray MD. 2015. Parvulescu revisited: small tank acoustics for bioacousticians. In: Popper AN, Hawkins AD (eds.) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press).

thresholds.[662] Standardisation in research studies will help to both define the sound field received but also allow for comparisons of source signals of different types.[663]

Current research programmes such as the International Quiet Ocean Experiment (IQOE)[664] and the Listening to the Deep Ocean (LIDO) project[665] are important elements in improving our understanding of underwater sound and anthropogenic noise in our oceans and need to be supported and expanded over the long-term.

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[662] Sisneros JA, Popper AN, Hawkins AD, Fay RR. 2015. Auditory evoked potential audiograms compared to behavioral audiograms in aquatic animals. In: Popper AN, Hawkins AD (eds) The effects of noise on aquatic life, II. Springer Science + Business Media, New York (in press)

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

[664] 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

[665] 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. Identified research needs for anthropogenic underwater noise and its impact on Marine Biodiversity (adapted from Boyd et al., 2008; Southall et al., 2009; Tasker et al., 2010, Hawkins et al., 2015)

Subject Area (s)	Research Needs
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 Establish sound monitoring stations and programmes to survey different underwater soundscapes that involve real-time monitoring and storage of raw data
	Determine the characteristics, distribution and abundance of anthropogenic sound sources in the marine environment Improve knowledge of the propagation of sound (both sound pressure and particle motion) Describe and fully evaluate the effects of sound fields produced by anthropogenic sound sources Establish a central data repository and standards/protocols for data collection
	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. Determine ecological thresholds for anthropogenic sounds – how much an environment can tolerate without its ecological status being changed
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 ability, especially for low frequency and high frequency species; • Modelling of the auditory system (to reduce dose response experimental exposure to sound). • Developing new tools to identify unknown biological sound sources and document associated behaviours Establish a library of sounds for marine animals to facilitate the use of passive acoustic tools
	Expand/improve distribution, abundance, behavioural and habitat data for marine species particularly susceptible to anthropogenic sound
	Expand/improve distribution, abundance, behavioural and habitat data for marine species with high potential susceptibility to anthropogenic sound

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
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, decompression sickness • Masking – communication and orientation • Particle motion impacts • Survival and reproductive success Accurate measurement of sound effects in experiments that adequately replicate the sound characteristics of man-made sources
	Investigate cumulative and aggregate effects of noise and stressors on marine organisms for both: • multiple exposures to sound (anthropogenic and natural) • sound in combination with other stressors
	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.
Measurement and description of sounds	Adoption of relevant and universally acceptable metrics that describe sound appropriately and enable comparison of sound effects for different sound types and taxa

	Development of a common terminology for sound measurement and exposure understandable to the whole community Developing inexpensive ‘non-specialist’ instrumentation for underwater sound measurement in the laboratory and in the field
The conduct of acoustic experiments	Development of special acoustic facilities to enable investigators to present sounds to animals with full specification of the signals presented both in the laboratory and in the field, and for both sound pressure and particle motion

6. CONCLUSIONS

The levels of anthropogenic noise in the marine environment have increased substantially in the last century[666] 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.[667] 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.[668]

Sound is extremely important to many marine animals and plays a key role in communication, navigation, orientation, feeding and the detection of predators.[669] From invertebrate larvae[670] to the largest animals on the planet,[671] 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-related impacts that can result in a substantial loss of biodiversity over time in sensitive marine habitats.[672] In combination with other stressors,underwater noise pollution is likely to contribute to marine defaunation, which is predicted to increase as human use of the oceans industrialises.[673]

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[674] 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.[675]

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

[667] 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

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[669] 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

[670] 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

[671] 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

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[673] McCauley, D.J., Pinsky, M.L., Palumbi, S.R. et al. 2015. Marine defaunation: Animal loss in the global ocean. Science 347. Doi: 10.1126/science.1255641

[674] 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

[675] 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[676,677], 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.[678] 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.[679] 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.[680] 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.[681] There is also growing concern of the cumulative effects of anthropogenic sound and other stressors and how this can affect populations and communities.[682]

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 predicted 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, as well ecologically or commercially important taxa.

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. These 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).

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

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[678] 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

[679] 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

[680] 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.

[681] 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.

[682] 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

already-stressed oceanic biota.[683] 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, on a global, regional and national scale, to implement adequate regulatory and management measures.

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[683] 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)

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,[684,685] 2. Giant squid (inferred) [686], 3. Humpback whale[687]
	Induction of gas embolism (Gas Embolic Syndrome, Decompression Sickness, 'the bends', Caisson syndrome)	Intense mid-frequency (Naval) sonar	Beaked whales, [688 , 689] odontocete cetaceans, [690] Harbour porpoise (inferred)[691]
	Induction of fat embolism	Intense mid-frequency (Naval) sonar	Beaked whales[692]
	Disruption of gas filled organs such as the swim bladder (fishes) [with consequent	Pile driving	Various fish species, [693] Chinook Salmon (juvenile)[694]

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
	damage to surrounding tissue]		
	Tissue and organ haemorrhaging and haematomas	Pile driving (simulated)	Chinook Salmon (juvenile),[695, 696] Hybrid striped bass,[697] Lake sturgeon, Nile tilapia[698]
	Body malformations during larval development, delayed larval / embryonic development or larval mortality	1. Seismic air guns (simulated), 2. Boat noise, 3 Offshore marine renewable energy – tidal turbine and wind turbine noise (simulated)	1. New Zealand scallop larvae,[699], 2. Sea Hare embryos and veliger larvae,[700] 3. Brachyuran crab megalopae[701]
	Endochrinological stress responses	1. Seismic air guns 2. Onshore aquaculture (simulated), 3. Shipping noise	1. Sea bass, [702] Atlantic Salmon, [703] Bottlenose dolphin and Beluga (simulated)[704], 2. Gilthead sea bream (juvenile)[705]. 3. European spiny lobster,[706,707] Shore crab[708]
Auditory	Gross damage to the auditory system e.g.,	1. Intense mid-frequency sonar, 2.	1. Beaked whales,[709] 2. Humpback whale[710]

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
(Sound induced hearing loss)	resulting in: rupture of the oval or round window or rupture of the ear drum	Explosions	
	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[711], 2. Spotted dolphin[712]
	Damage to the sensory hair cells Damage to statocysts (cephalopods)	1. Air guns (actual and simulated), 2. Pile driving (simulated), 3. Low frequency sounds (shipping proxy)	1. Various fin-fish,[713] Pink snapper,[714] Cephalopods (four species), [715] 2. Hybrid striped bass, [716] 3 Cephalopods (four species)[717]
	Permanent hearing threshold shift (PTS) i.e. a permanent elevation of the level at which a sound can be detected	1. Air guns (modelled), 2. Sonar (simulated), 3. Pile driving	1. Baleen whales,[718] 2. Harbour seal,[719] 3. Harbour seal[720]
	Temporary hearing threshold shift (TTS) i.e. a temporary elevation of the level at which a	1. Air guns (modelled), 2. Mid-frequency sonar (simulated), 3.	1. Baleen whales, [721] Harbour porpoise, [722] 2. Bottlenose dolphin, [723] channel catfish, [724] 3.

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
	sound can be detected	Ice breaker (modelled), 4. Low frequency sonar (simulated), 5. Pile driving (simulated)	Beluga, [725] 4. channel catfish, [726] 5. Harbour porpoises[727]
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, [728] 3. Delphinid cetaceans, [729] Fish: Sciaenid, Pomacentrid and Goby, [730] Killer whale (modelled), [731] Pacific humpback dolphin[732] 4. Beluga (modelled), [733] 5. Humpback whale[734]
	Masking of other biologically important sounds including orientation and settlement cues, echolocation signals	Shipping	Cuvier's beaked whale[735]
Behavioural	Stranding or beaching	1. Intense low or mid-frequency (Naval) sonar, 2. Multi-beam	1. Beaked whales,[736,737,738,739,740,741], Short finned pilot whale,[742,743] Pygmy sperm whale,[744] Pygmy

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
		echosounder system	killer whale,[745] Minke whale,[746, 747] Hawaiian melon-headed whale[748], common dolphin (inferred),[749] 2. Melon-headed whale[750]
	Behaviour modified (e.g. less effective / efficient)	1. Shipping (simulated), 2. boat noise	1. Sea bass and sea bream,[751] European eel,[752] three-spined stickleback, European minnow[753,754], Shore crab[755], 2. coral reef fish larvae,[756], Mediterranean damselfish[757]
	Behaviourally-mediated effects including	1. Acoustic deterrents, 2. Recreational vessels, 3. Over	1. Harbour porpoise[758, 759] 2. Bottlenose dolphin,[760, 761] Bluefin tuna,[762] Killer whale,[763]

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
	avoidance,	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, 13. Research vessels, 14. Experimental sound treatments, 15. Shipping, 16.	Humpback whale[764] 9. Killer whales,[765,766] Hooded seals,[767] Gray Whales[768], Cuvier's beaked whale,[769] Baird's beaked whale, [770] Blue whale, [771] Delphinids, [772] Sperm and long-finned pilot whales [773] 10. Bowhead whales, [774] humpback whales, turtles, fish and squid, [775] Pelagic fish – herring, blue whiting and others, [776] Various Cetaceans,[777] five marine fish species and southern reef squid [778] 11. Cod and sole, [779] Harbour

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
		Shipping/Boat noise (simulated)	porpoises,[780,781] Mackerel and sprats[782]12. Beluga[783] 13. Various marine fish spp[784], 14. European sea bass [785], 15. Killer whales (modelled) [786], 16. European spiny lobster[787], common cuttlefish[788], Bryozoan larvae[789], Green-lipped mussel larvae[790]
	Adaptive shifting of vocalisation intensity	1. Shipping, 2. Recreational vessels, 3. Air guns, 4. Intense	1. Right whale[791], 2. Killer whale,[792] Beluga,[793] Fin whale,[794,795] Blue whale[796] 3. Sperm whale,[797] Fin

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
	and/or frequency including cessation of calls	low or mid-frequency sonar, 5. Acoustic devices. 6. Acoustic experiments	whale,[798] Harbour porpoise,[799] 4. Long finned pilot whale,[800,801] Blue[802] and fin whale[803], Humpback whale[804,805], Sperm whale[806], Blainville's beaked whales,[807] Killer whale,[808] 5. Sperm whale,[809,810] 6. Humpback whale[811]
	Interruption of normal behaviour such as feeding, breeding or nursing	1. Recreational or other vessels, 2. Air guns, 3. intense low or	1. Killer whale, [812] Manatee, [813] Damselfish, [814] Cuvier's beaked whale,[815] 2. Sperm whale[816,817], 3.

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Impact	Type of effect	Type of Anthropogenic Noise	Marine organisms affected
		mid-frequency sonar, 4 pile driving (simulated), 5. Shipping (drilling, explosions, dredging, high-frequency sonar, pile driving, shipping)	Blainville's beaked whales[818] 4. European sea bass (feeding)[819], 5. Blainville's beaked whales[820]
	Short-term or long-term displacement from area (habitat displacement)	1. tourism vessels, 2. Acoustic deterrents, 3. Shipping and/or drilling, 4. Air-guns (Bottom-towed fishing gear, dredging, air guns)	1. Bottlenose dolphin[821], 2. Killer whale[822], 3. Gray whale [823], Bowhead whale[824], 4. Fin whale[825]

Notes:

1. 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
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