MEASURES FOR REDUCTION OF ANTHROPOGENIC NOISE IN THE BALTIC

Report to the HELCOM SOM project

Scientific Report from DCE – Danish Centre for Environment and Energy No. 556 2023

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

MEASURES FOR REDUCTION OF ANTHROPOGENIC NOISE IN THE BALTIC

Report to the HELCOM SOM project

Scientific Report from DCE – Danish Centre for Environment and Energy No. 556 2023

Luca Lamoni
Jakob Tougaard

Aarhus University, Department of Ecoscience

AARHUS
UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

Data sheet

Series title and no.:	Scientific Report from DCE – Danish Centre for Environment and Energy No. 556
Title:	Measures for reduction of anthropogenic noise in the Baltic
Subtitle:	Report to the HELCOM SOM project
Authors:	Luca Lamoni
	Jakob Tougaard
Institution(s):	Aarhus University, Department of Ecoscience
Publisher:	Aarhus University, DCE – Danish Centre for Environment and Energy ©
URL:	http://dce.au.dk/en
Year of publication:	May 2023
Referee:	Charlotte Findlay
Quality assurance, DCE:	Jesper Fredshavn
Financial support:	The Danish Ministry of Environment
Please cite as:	Lamoni, L. & Tougaard, J. 2023. Measures for reduction of anthropogenic noise in the Baltic. Report to the HELCOM SOM project. Aarhus University, DCE – Danish Centre for Environment and Energy, 61 pp. Scientific Report No. 556
	Reproduction permitted provided the source is explicitly acknowledged

Abstract:	The recent update of the HELCOM Baltic Sea Action Plan in has created an urgent need for reviewing the major sources of underwater noise, their known and likely impact on the marine environment and possible ways to mitigate the impact. Impulsive noise sources (pile driving, seismic surveys, underwater explosions, low-frequency sonars etc.) are known to cause negative effects in marine mammals and fish. Mitigation includes: a) reduction in produced noise (source modification), b) reduction in radiated noise (abatement) and c) reduction in received noise (restriction of activities in sensitive areas and periods, deterrence from dangerous zones prior to impact). Continuous low-frequency noise is predominantly generated by commercial vessels and recreational boating, with additional contribution from offshore infrastructure (oil and gas, renewables). Mitigation measures are primarily source modification (improving design and operational procedures/speed reduction) and time/area restrictions (including regional/local speed limits and/or requirements for vessels to abide by specific noise emission standards). Additional sources currently not monitored include echosounders and high frequency sonars, net pingers and seal scarers, and equipment other than air guns for exploring the uppermost layers of the seabed (subbottom profiling and surveying).

Keywords:	Underwater noise, HELCOM, Baltic Sea Action Plan, marine mammals
Front page photo:	John Robert McPherson/Wikimedia Commons
ISBN:	978-87-7156-780-9
ISSN (electronic):	2245-0203
Number of pages:	61

Contents

Preface

HELCOM updated the Baltic Sea Action Plan (BSAP) in 2022. Several processes fed into this update and one of these were the Sufficiency of Measures (SOM) platform project, which evaluated the level of implementation and efficiency of actions from the preceding BSAP. Underwater noise, however, was not part of the old BSAP.

In parallel with the SOM-Platform project and update of the BSAP has been the development of a HELCOM Regional Action Plan (RAP) on underwater noise in the Baltic, developed by the expert network, EN-Noise. The underwater noise RAP was adopted as a HELCOM recommendation in 2021.

This report collects the background documentation that was used as input to both the SOM-Platform project and the RAP. The main focus has been on effects on marine mammals and to a lesser degree on fish, reflecting the similar differences in the level of knowledge about impacts. Although negative effects of underwater noise on invertebrates are well documented too, the current knowledge regarding effects on invertebrates is not at a level, where general conclusions can be drawn and they have thus been excluded from this review.

The work was funded through a contract with the Danish Ministry for Environment and Agriculture.

Sammenfatning

I tiden mellem den første handlingsplan for Østersøen (Baltic Sea Action Plan) blev vedtaget i 2007 og den nyligt reviderede plan fra 2021, er undervandsstøj kommet på dagsordenen og blevet anerkendt som en vigtig presfaktor på det marine miljø. Dette har skabt et behov for en gennemgang af de vigtigste kilder til undervandsstøj, deres påvirkning på marine organismer og mulige måder at reducere/afværge påvirkningerne.

Med vedtagelsen af det Europæiske Havstrategidirektiv blev dette til den væsentligste kilde i defineringen af mål og metoder til regulering af undervandsstøj i Europæiske havområder, herunder Østersøen. Et nøgleelement i Havstrategidirektivet er opdelingen af støjkilder i to hovedgrupper: impulsstøj og vedvarende støj. Talrige øvrige kilder er ikke omfattet af disse to kategorier, hvilket har ført til en tredje kategori af "øvrige lydkilder".

Impulsstøj

Kilder til impulsstøj omfatter pæleramning, seismiske undersøgelser med luftkanoner, undervandseksplosioner og lavfrekvente sonarsystemer. Alle disse kilder er kendt for at kunne påvirke havpattedyr og fisk negativt. Effekterne rækker fra forstyrrelse af adfærd og fortrængning til vævsskade, og i yderste fald død. Da disse kilder er meget udbredte er der et udtalt behov for afværgeforanstaltninger.

Afværgeforanstaltninger for impulsstøj følger tre generelle principper for reduktion af påvirkning fra støj: reduktion af den producerede støj (modificering af kilden), reduktion af den udstrålede støj (afskærmning) og reduktion af den modtagne støj (begrænsning af aktiviteter i følsomme områder og perioder, bortskræmning forud for anvendelse). De tre metoder udelukker ikke hinanden, men kan anvendes sideløbende for at øge effekten.

De mulige ændringer af lydkilden for impulsstøj er specifikke for de enkelte støjkilder, og dækker over at reducere den udstrålede effekt til det minimale niveau krævet for at løse opgaven, og at ændre udstyr og procedurer for at minimere støj, der er et produkt af den primære aktivitet (f.eks. pæleramning, hvor støjen ikke tjener noget formål), og skifte teknologi til mindre støjende alternativer (fx fundamenter, der ikke kræver pæleramning og fjernelse af ueksploderet ammunition ved andre metoder end bortsprængning).

Afskærmning af impulsstøjkilder er hovedsageligt begrænset til aktiviteter, hvor støjudsendelsen ikke sker med et formål i sig selv, som f.eks. pæleramning og eksplosioner. Flere typer af effektive afskærmingssystemer er tilgængelige, baseret på luftboblegardiner eller andre typer af absorberende materialer, der kan fungere som afskærmning mellem kilden og modtagerne (dyrene).

Planlægning af aktiviteter i tid og rum kan være særdeles effektiv til at nedsætte den samlede påvirkning på bestandsniveau, ved at henvise (om muligt) aktiviteterne til områder af mindre betydning for dyrene og/eller til perioder på dagen eller året, hvor dyrene er mindre følsomme for påvirkning fra støjen.

Vedvarende lavfrekvent støj

Samlet set er fragtskibe den mest betydelige kilde til lavfrekvent undervandsstøj, hvorfor størst opmærksomhed har været rettet mod negative effekter af skibsstøj. Andre kilder kan dog være af samme eller endog større lokal/regional betydning, i særlig grad drift af offshore infrastruktur (olie- og gasplatforme og vedvarende energiinstallationer), samt private både.

Fælles for disse kilder er at de er talrige, og i de fleste tilfælde mobile, og udsender støj mere eller mindre kontinuerligt. Dette gør at afværgeforanstaltninger primært begrænser sig til modifikationer af støjkilden, og til restriktioner i rum og tid, idet afskærmning i de fleste tilfælde er af begrænset værdi. For skibes vedkommende kan den udstrålede støj reduceres ved at optimere design, vedligehold og driftsmønstre af skrog, propeller og maskiner, men også simpelthen ved at sætte farten ned. Dette gør, at en række muligheder for regulering og forvaltning er til stede for betydningsfulde og/eller sårbare områder, idet påvirkning fra støjen kan nedbringes, ikke bare ved begrænsninger i rum og tid, men også mindre indgribende tiltag, såsom regionale/lokale hastighedsgrænser, evt. i kombination med krav om overholdelse af særlige standarder (klassificeringer) for støjudsendelse.

Andre støjkilder

De nuværende indikatorer for undervandsstøj i HELCOMs overvågningsprogram og støjkriterierne i Havstrategidirektivet omfatter ikke alle støjkilder, der potentielt kan påvirke havmiljøet negativt. Der er derfor behov for fortsatte undersøgelser for at afdække udbredelsen af disse støjkilder, og for at kvantificere og forstå effekten på marine organismer.

Blandt de mest udbredte menneskeskabte støjkilder i havet er ekkolod og kommercielle sonarsystemer. De fleste af disse systemer er karakteriseret ved en relativt lille påvirkning på grund af moderate kildestyrker, og ofte meget smalle, nedadrettede udstrålingsmønstre. Den primære årsag til bekymring for påvirkning er derfor det store antal, den store udbredelse og det faktum at de ofte er tændt konstant (lovkrav på kommercielle skibe). Andre systemer, herunder visse sonarsystemer, kan have kraftigere lydstråler, der er rettet fremad eller til siden ift. skibets sejlretning og dermed har større potentiale for påvirkning af omgivelserne.

Potentielle negative effekter af ekkolod mm. kan afværges og begrænses på forskellig vis. Afhængigt af kravene til systemets anvendelse kan designet ændres, med ændrede signalegenskaber og dermed mindre potentiale for påvirkning af sårbare arter. Centralt er imidlertid også måden udstyret anvendes på, hvor man vil kunne ændre udsendingen af lyd adaptivt, afhængigt af de øjeblikkelige forhold. Sådanne tilpasninger kunne være i signalfrekvens, kildestyrke, signalvarighed og repetitionsrate.

Garnpingere og sælskræmmere er beregnet til at holde havpattedyr væk fra fiskeredskaber og havbrug. Dette kan imidlertid skabe uønskede sideeffekter, i form af uforholdsmæssig stor forstyrrelse og fortrængning, ud over hvad der kræves for at opfylde det primære formål med udstyret. Der er således behov for udvikling af svagere pingere, kun hørbare i den umiddelbare nærhed af garnet, hvilket vil reducere både habitattab og støjforurening i det hele taget. Sælskræmmere er meget kraftigere og kan forstyrre havpattedyr over store afstande. Der er således behov for målrettet regulering af deres brug, således at behovet for at holde sæler væk fra fiskeriudstyr afbalanceres med den uønskede fortrængning af dyr på større afstand.

En sidste gruppe af lydkilder, der ikke har haft større opmærksomhed, er udstyr til geoakustiske undersøgelser af de øverste lag i havbunden, ud over udstyr med luftkanoner (der er inkluderet under impulsstøjkilder ovenfor). Sådanne systemer har potentiale for betydelig påvirkning lokalt omkring opmålingen og undersøgelser er derfor nødvendige for at kortlægge omfanget af brugen af dette udstyr og måder at reducere påvirkningen på, gennem teknologiske ændringer og/eller ændringer i anvendelsen.

Summary

Since the first Baltic Sea Action Plan (BSAP) was adopted in 2007 and the present updated action plan from 2021, underwater noise has entered as an acknowledged pressure on the Baltic Sea marine environment. This creates an urgent need for reviewing the major sources of underwater noise, their known and likely impact on the marine environment and possible ways to mitigate the impact.

Since the endorsement of the European Union Marine Strategy Framework Directive (MSFD), this document has been the key framework defining regulation of underwater noise in European waters, including the Baltic Sea. A key element in the MSFD is the division of noise sources into two major categories: impulsive noise and continuous noise. Numerous additional sources of underwater noise are not covered by these two categories, which leads to a third, 'Other' category.

Impulsive noise

Sources of impulsive noise include pile driving, seismic surveys involving airguns, underwater explosions and low-frequency sonars and all of these sources are known to cause negative effects in marine mammals and fish. These effects range from disturbance and deterrence, to bodily injury and in extreme cases even death and due to the widespread use of these impulsive sources, mitigating measures are required.

Mitigation of impulsive noise follows the general three principles for reducing impact: reduction in produced noise (source modification), reduction in radiated noise (abatement) and reduction in received noise (restriction of activities in sensitive areas and periods, deterrence from dangerous zones prior to impact). The three methods are not mutually exclusive, but can be combined and thereby increase the overall mitigation achieved.

Source modifications for impulsive noise is source specific and relies on reducing overall radiated power to the minimally required level for accomplishing the task; modifying equipment and procedures to reduce radiated noise as a by-product of the primary activity (such as for pile driving, where the noise serves no role in itself); and changing technology to quieter alternatives (foundations not relying on pile driving for installations, destruction of explosives (unexplored ordnance) with methods other than detonation).

Noise abatement for impulsive sources is largely restricted to sources where the sound is not emitted for a purpose, such as pile driving and explosions. Several types of efficient abatement techniques are available, involving air bubble curtains or other types of absorptive materials used as a shield between the source and the receivers (the animals).

Extensive time-area planning is highly useful in reducing the overall impact on populations of animals, by restricting activities (when possible) to areas of lesser importance to the animals and/or to times of the day or year, where the animals are less sensitive to impact from noise.

Continuous low-frequency noise

The overall most important source of continuous low-frequency noise is commercial vessels, which is why most attention has been directed at impact from ships. Other sources can be of similar or even larger local/regional importance, most importantly operation of offshore infrastructure (oil and gas platforms, offshore renewables) and recreational boating.

Common for these sources are that they are numerous, in most cases mobile, and more or less continuously emitting noise. These factors limit the mitigation measures primarily to source modification and time/area restrictions, as abatement techniques in most cases are less feasible. For ships and boats the radiated noise can be reduced by improving design, maintenance and operation of the hull, propellers and engines, but also simply by reducing speed. This means that there are several tools available in management of important/sensitive areas, as the impact from noise can be reduced by not only time/area exclusion, but also less restrictive measures such as regional/local speed limits and/or requirements for vessels to abide by specific noise emission standards.

Other noise sources

The current indicators of the HELCOM monitoring program related to underwater noise, as well as the criteria of the MSFD, do not cover all noise sources that could potentially affect marine life detrimentally. There is thus a need for continuous research into the extent of these noise sources (mapping the pressure on the ecosystems) and understanding the effects of these noise sources on the organisms (mapping the impact).

Some of the most ubiquitous sound sources present in our oceans today are echosounders and other commercial shipboard sonar systems. Many of these systems are characterised by a relatively small footprint, due to moderate source levels and highly directional, downward-facing beams. The primary concern for impact from such systems comes because of the sheer number of systems installed and their continuous operation (required by law on commercial vessels). Other systems, including various sonars, have more powerful beams that are directed forwards or sideways from the ship and thereby have larger potential for impact.

Potential impact of sonars and echosounders can be mitigated in various ways. Depending on the use of the instrument, the design can be changed, with altered signal properties and thereby less potential for impact on marine life. Central, however, is also adjustable operation modes, allowing adaptation of the emissions to the circumstances. Such adaptations include changes of signal frequency, source level, ping duration and ping rate.

Net pingers and seal scarers are devices used to deter odontocetes and seals from fishing gear, aquaculture and construction installations. This creates unwanted side effects in the form of additional disturbance and displacement, beyond what is required to meet the primary purpose of the device. Future research should be focused on the development of low source level net pingers that could be audible only within close range of the net; this would reduce noise pollution as well as habitat loss. Seal scarers, on the other hand, are more powerful and able to disturb marine mammals over great distances. Specific regulation for their use is likely required, to balance the needs for deterrence with the unintended displacement at long range.

A last group of sound source that has received relatively little attention is equipment other than airguns (as they are included under impulsive sources above) for seismic exploration of the seabed (sub-bottom profilers and their like). Such systems have potential for significant impact on a local scale and research is required in order to map the potential impact from these devices and ways to mitigate the impact, through technological developments and/or modifications to the way they are operated.

1 HELCOM and underwater noise

Between the old Baltic Sea Action Plan (BSAP), adopted in 2007 and the updated action plan from 2021, there has been a large development in respect to monitoring, assessment and regulation of underwater noise. Underwater noise was thus not recognized explicitly as a pressure factor in the BSAP2007, but has been so subsequently as a consequence of implementation of the EU Habitats directive (European Commission, 2008). Central in this implementation was the decision by the HELCOM Ministerial Meeting in 2013 to establish a monitoring and assessment program for underwater noise and the commitment by the 2018 Ministerial Meeting to develop and implement a Regional Action Plan on underwater noise.

In brief, the status of implementation of these decisions are that two indicators of underwater noise have been implemented as pre-CORE indicators in the HELCOM monitoring program. These indicators have been developed to be in accordance with recommendations from the EU Commission (2017) regarding implementation of the MSFD criteria D11C1 (impulsive noise) and D11C2 (continuous, low-frequency noise). Details can be found in the HELCOM documentation for the monitoring programs (link).

Furthermore, the HELCOM Regional Action Plan for underwater noise was adopted by HELCOM in 2021 (HELCOM, 2021b). The RAP lists and describes 35 actions to be implemented at the regional level, as well as 17 actions to be implemented nationally. Additional actions directed towards reducing the impact of underwater noise are included in the BSAP2021, as actions S55 to S63 (HELCOM, 2021a).

2 Actions directed at impulsive noise

Impulsive noise is poorly defined in the context of MSFD, but from guidance documents from the EU expert group on underwater noise (TG-Noise) it is clear that the primary sources are pile driving, seismic surveys involving airguns, underwater explosions and low-frequency sonars (Dekeling et al., 2014). All of these sources are known to cause negative effects in marine mammals and fish, ranging from disturbance and deterrence to bodily injury and in extreme cases (such as explosions) even death. There is thus a need for tools to regulate activities and methods for mitigating detrimental effects. In the following, the four main sources of impulsive noise are discussed, in particular with respect to actions that can potentially reduce impact.

2.1 Pile driving

Pile driving of large steel monopiles in offshore waters has increased rapidly in recent years due to the expanding development of offshore wind energy. Already by 2019 there were more than 4500 grid-connected offshore wind turbines across eleven countries, equivalent to a capacity of 18 499 MW (WindEurope, 2019). The large steel monopiles most commonly used as foundation for the wind turbines are usually driven 20-30 m into the seabed with hydraulic hammers, which generates very high amplitude impulsive sounds. Source levels between 235 dB re 1 μPa_{pp} and 262 dB dB_{pp} re 1 µPa at 1 m in 10 m water depth have been estimated (Nedwell et al., 2003; Tougaard et al., 2009; Bellmann et al., 2020). Noise from pile driving can be detectable at distances of tens of km (Tougaard et al., 2009; Bailey et al., 2010; Tougaard et al., 2012). The single pulses are between 50 and 100 ms in duration with approximately 35-65 strikes per minute (Kastelein et al., 2013). At close range (up to 2 km distance from the piling source), the noise is highly broadband. Peak sound energy occurs between 100 Hz to 2 kHz, but a significant amount of energy can be found also at higher frequencies, up to 100 kHz (Tougaard et al., 2009; Bailey et al., 2010).

Several studies have looked at the effects of pile driving noise on harbour porpoises. Harbour porpoise echolocation activity has been shown to decrease significantly within 11-21 km from pile driving locations (Tougaard et al., 2009; Brandt et al., 2011; Dähne et al., 2013). Dähne et al. (2013) also conducted aerial surveys and reported strong harbour porpoise avoidance within 20 km from pile driving activity. In studies on animals in captivity, it has also been shown that pile driving noise can cause a decrease in foraging efficiency. Kastelein et al. (2019) tested two captive harbour porpoises with a fish-catching task (i.e. retrieving dead fish from a net feeding cage) under quiet and noisy acoustic conditions (sound exposure levels, SELs, between 125 and 143 dB re 1 μPa^2s). Physiological responses have also been recorded in captive harbour porpoises exposed to pile driving playbacks (46 strikes/min) at five sound pressure levels (SPLs) (6 dB steps: 130–154 dB re 1 µPa). The respiration rate increased in response to the pile driving sounds (Kastelein et al., 2013; Kastelein et al., 2022). At the highest sound pressure levels, startle-like response were also seen, with animal jumping out of the water more often than without sound present.

Harbour seals seem to present similar avoidance behaviours when exposed to pile driving noise. Using telemetry data, Russell et al. (2016) measured a 19-

85% significant decrease in seal abundance within 25 km of the centre of the wind farm. This displacement started at predicted received levels between 166 and 178 dB re 1 μPa_{pp} and was limited to the piling activity; within 2 h of cessation of pile driving, seals were distributed as per the non-piling scenario. Similar results have been found in grey seals (Aarts et al., 2017). Edrén et al. (2010) furthermore reported that during pile driving activity, a significant short-term decrease in the number of seals present at a haul-out site 4 km away from the wind farm location.

Effects of pile driving on fish physiology and behaviour have also been documented. Hybrid striped bass (*Morone* spp.) and Mozambique *Tilapia* (*Oreochromis* spp.) exposed to 960 pile driving strikes at one of three treatment levels (cumulative SEL: 216, 213, or 210 dB re 1 μPa^2s) showed significant barotraumas including swim bladder ruptures, herniations, and hematomas to several organs (Casper et al., 2013). Damages to inner ear hair cells occurred only at the higher SEL (and not at the lower ones) for the hybrid striped bass, but only occasionally for the *Tilapia*. The authors suggest that pile driving sounds, at the levels tested in this study, may have a more significant effect on the swim bladders and surrounding organs than on the inner ears of fishes. Similar swim bladder injuries were also reported for lake sturgeon (*Acipenser fulvescens*), Nile tilapia (*Oreochromis niloticus*) (Halvorsen et al., 2012a) and Chinook salmon (*Oncorhynchus tshawytscha*) (Halvorsen et al., 2012b).

Pile driving noise at lower amplitudes triggers behavioural responses in fish. For example, group cohesion and directional correlation among juvenile seabass (*Dicentrarchus labrax*) individuals have been shown to be negatively impacted by pile driving noise (Herbert-Read et al., 2017). In another study, seabass exposed to pile driving playbacks showed also startle responses (SPL 164 dB re 1 μPa_{0-p}), higher stress levels (increased ventilation rates) and disrupted anti-predator behaviours (mean peak sound pressure was 152 ± 3.5 dB re 1 μPa_{rms}) (Spiga et al., 2017). Startle responses as well as body pattern changes, inking and jetting were observed when exposing individual squids (*Doryteuthis pealeii*) to pile driving recordings (Jones et al., 2020). An experiment conducted in the wild revealed that in schools of sprat (*Sprattus sprattus*) and mackerel (*Scomber scombrus*) behavioural responses increased with increased sound levels. These responses included increased dispersion (sprat) and changes in depth (mackerel). The sound pressure levels to which the fish schools responded on 50% of presentations were 163.2 and 163.3 dB re 1 μPa_{pp}, and the single strike sound exposure levels were 135.0 and 142.0 dB re 1 μPa^2s, for sprat and mackerel, respectively (Hawkins et al., 2014).

2.1.1 Mitigation

Several countries in Europe have introduced legal restrictions for underwater noise to protect marine wildlife and therefore there is an increasing need to mitigate various forms of underwater noise. For example, in German waters a mandatory threshold of 160 dB (SEL, single pulse) and 190 dB (peak-to-peak) at a distance of 750 m during pile driving has been established in 2008 for the protection of marine mammals (German Federal Ministry for the Environment and Nuclear Safety, 2013; Koschinski and Lüdemann, 2020). In other countries, such as Denmark, there is no fixed exposure limits, but exposure to individual marine mammals during pile driving of a single monopile are not allowed to exceed the levels associated with an increased risk of noise-induced permanent hearing loss (Danish Energy Agency, 2022). The exposure is to be quantified as auditory frequency weighted and cumulated sound exposure level, compared to the PTS-onset thresholds provided by (Southall et al., 2019). Today the implementation of technical noise mitigation systems is a standard requirement at offshore construction sites in many countries, being considered Best Available Technology (BAT). Several technical noise mitigation systems listed below have the potential to reduce noise emissions during impact pile driving of offshore wind turbine foundations. Several of these systems have the potential to be used in combination, thus increasing the overall noise mitigation performance.

2.1.2 Bubble curtains

Despite several available solutions, the air-bubble curtain is usually preferred due to the simplicity in its application in an offshore setting and the efficacy in the noise reduction (Tsouvalas and Metrikine, 2016). A curtain of air bubbles around the pile driving activity has been shown to reduce the noise outside of the immediate area of construction. The first to test bubble curtains in pile driving construction were Würsig et al. (2000), they recorded a 3-5 dB noise reduction, predominantly in the 400 to 6400 Hz band, when bubble curtains were active. This mitigation measure has been tested widely, Bellmann (2014) reported the testing of more than 20 different system configurations of (single and double) air-bubble curtains systems across more than 600 foundation installations in nine different offshore wind farms.

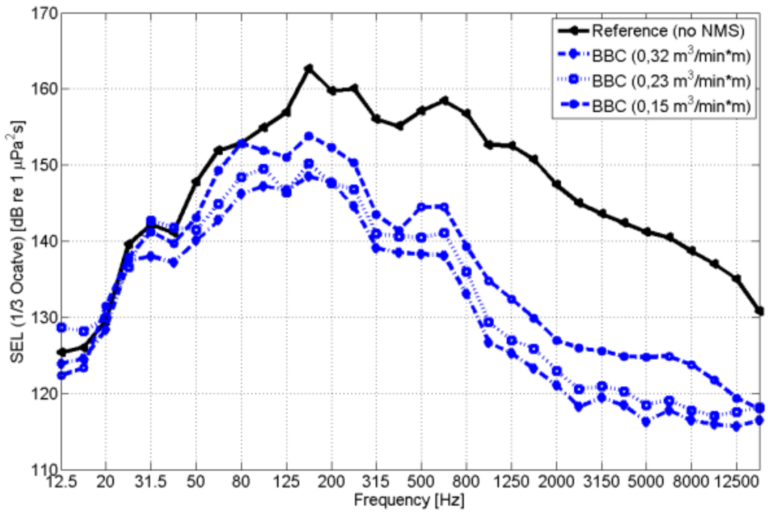

Figure 2.1. Graph taken from (Bellmann et al., 2014) with an example of the 1/3 octave spectra of the median sound exposure level (SEL) with and without a Big Bubble Curtain (BBC) in different system configuration (used supplied air volume) measured at a distance of 750 m from the pile.

Based on this data, Bellmann (2014) reported that piling noise SEL could be reduced by 10-18 dB, depending on the diameter of the pile and the bubble curtain configuration. Similar results were also obtained in 2007 during a Ferry Terminal pile driving construction in which average sound reductions achieved with the bubble curtains ranged from 3 to 11 dB (Sexton, 2007). A more recent publication reported SEL reductions up to 15 dB (depth 25 m) for single bubble curtains and up for 18 dB (depth 40 m) for double bubble curtains (Koschinski and Lüdemann, 2020). See also Bellmann et al. (2020) for most recently updated measurements. Theoretical models have been developed to select the most effective bubble curtain setup based on the diameter of the piles, the acoustic characteristics of the piling noise emitted and the volume of air available to produce the curtain (Tsouvalas and Metrikine, 2016).

2.1.3 Hydro Sound Dampers (HSD)

The Hydro Sound Damper (HSD) is a versatile method to reduce noise levels during offshore pile driving. HSD systems use fishing nets around the pile, the net is equipped with gas filled elastic balloons and special PE-foam elements with high dissipative effects to reduce continuous and impact noise. The advantage of this method, compared to air-bubble curtains, is that it is independent of external air supply, it is not influenced by tidal currents, it is less expensive and, in general, easily adaptable to different pile deployments. HSD have been successfully applied on more than 340 piles in various commercial offshore wind farms at water depths up to 45 m and with pile diameters up to 8 m with a very low rate of malfunctions (<1%; Koschinski and Lüdemann, 2020). Results suggest that piling noise can be effectively decreased by 10 – 20 dB in the 100 – 1000 Hz band (Kuhn et al., 2012; Bruns et al., 2014), even at great depth (SEL reduction 10 - 13 dB, at 40-60 m water depth; Elmer, 2018). HSD can also be used in combination with air-bubble curtains, reaching an even higher reduction in SEL, between 19 and 24 dB, with a pile diameter of 7.8 m and at a water depth of 40 m (Elmer, 2018).

2.1.4 Isolation Casings

An isolation casing is a shell-in-shell system around the pile that help reduce radiated noise. Piles are inserted from the top into an Integrated Monopile Installer, that features an acoustically decoupled double wall with an air-filled interspace and a bubble curtain inside the casing which reduces coupling of sound pressure waves to the steel shells by absorption, scattering and dissipation effects (Koschinski and Lüdemann, 2020). Until now, this system has been applied in over 450 pile installations for pile diameters up to 8 m. It can be completely integrated into the installation process keeping installation time short. Isolation casings can be employed at water depths up to 45 m. By combining several principles of noise reduction in various layers around the pile, isolation casings are capable of a high noise reduction comparable to or exceeding that of a bubble curtain. The noise reduction measured in various commercial offshore wind farms projects was in the range of 13 to 16 dB (SEL) even at a water depth of up to 40 m. At frequencies higher than 500 Hz, the isolation casings can achieve noise reductions up to 40 dB (Koschinski and Lüdemann, 2020).

2.1.5 Cofferdams

A cofferdam is a steel tube surrounding the pile from the seabed to the surface. In practice, the cofferdam isolates the pile vibrations from water by means of a cylindrical air gap and thus it effectively reduces sound energy propagation. During 2011 and 2012, full scale prototype monopiles have been installed using cofferdams in Aarhus Bight (pile length 36 m, pile diameter 2.13 m, cofferdam diameter 2.5 m, water depth 15 m; McKenzie Maxon, 2012). The measurements collected during this prototypes' deployment confirmed that this mitigation methods can significantly reduce piling noise propagation (SEL reduction up to 23 dB). However, in a concurrent test deployment, the seal between the cofferdams air gap and the external water failed resulting in a reduced mitigation performance (SEL 13 dB). This potential weakness of cofferdams decreased the industry's confidence in this otherwise very promising method; Koschinski and Lüdemann (2020) report no cofferdams currently deployed in offshore wind farm constructions.

2.1.6 BLUE piling

The BLUE piling method uses the principle of pulse prolongation. The BLUE 25M hammer uses a large water column to generate the driving force. Seawater inside a steel tube closed at the bottom is pushed upwards and allowed to fall on the pile resulting in the pulse that drives the pile in the ground. This cycle is repeated until the pile reaches its desired depth. Using this piling method, the pulse duration can be increased by a factor of 20 compared to a hydraulic hammer. When the impact energy is distributed over a longer period, the maximum impact force and thus the amplitude of the lateral extension of the pile is reduced (Koschinski and Lüdemann, 2020). The bandwidth of the noise emitted during BLUE piling is lower than for percussive piling because the oscillation period of compression waves in the pile is prolonged. The reduced propagation velocity of the lateral extension directly decreases the sound emission. Several nearshore and offshore tests with various hammer sizes have been conducted. In a recent test in 2018, the BLUE 25M hammer prototype could be tested: the blows were about 100 ms long (compared to about 8 ms of a hydraulic hammer) using a pile with a 6.5 m diameter. Noise reduction in third octave level bands between 100 Hz and 4 kHz were 24 dB (SEL) lower compared to a reference pile driven conventionally in the same waters. For broadband values (10 Hz-20 kHz) the SEL reduction was 19-24 dB (Koschinski and Lüdemann, 2020).

2.1.7 Vibropiling

Vibropiling is a technique using flexural oscillations that reduce cohesion in the pile-soil boundary enabling an easier penetration into a sandy seabed. The main energy is radiated at lower frequencies compared to impact piling. In various offshore wind farm constructions, the technique has been applied in combination with impact piling. Vibropiling can be significantly faster and noise levels are reduced compared to impact piling. The frequency spectrum shows strongest noise emissions at the frequency of 17 to 18 Hz and its harmonics. Noise emissions from vibropiling are in the order of 10 to 20 dB ($L_{eq,30s}$) below mitigated impact pile driving at identical monopiles (Koschinski and Lüdemann, 2020). Depending on conservation objectives, a combination of vibropiling and impact piling may contribute to overall reductions in the noise budget as the installation is quicker and fewer strikes are needed for subsequent impact piling. Combined with impact piling, vibropiling has been proven effective in various offshore wind farm construction. Vibropiling is reliable, it has short installation time, lower energy demands and material savings. Therefore, foundation piles exclusively driven with vibro hammers can be a more cost-effective method which generates lower noise levels compared to impact piling (Koschinski and Lüdemann, 2020). However, it must be considered that vibropiling produces continuous noise, and therefore the potential acoustic impact on marine animals, compared to impulsive noise, might need to be reassessed.

2.1.8 Alternative low-noise foundation methods

Hard substrates cannot be penetrated by impact piling and therefore alternative low-noise foundation methods must be used to install the piles. One method is vertical drilling, which generates continuous noise, generally with lower levels that impact piling (estimated SEL of 117 dB at 750 m).

Noise emission from other methods such as gravity base foundations, suction bucket jacket (SBJ), and mono bucket foundation, are either equivalent or lower than ambient noise. The noise emission pertaining to these methods are usually limited to the noise from the ships linked to construction and suction pumps used in different ways, depending on the foundation construction method (Koschinski and Lüdemann, 2020).

2.2 Military sonars

Naval mid-frequency active sonar (MFAS) was developed in the 1950s to detect submarines, using frequencies of 8 KHz or higher (D'Amico et al., 2009). Following this initial development, MFAS operational frequencies were shifted to lower frequency ranges of 4.5–5.5 kHz. This change in frequency coincided with a significant increase in mass stranding events of beaked whales, which were extremely rare prior to the 1960s (only 15 cases reported; Bernaldo de Quiros et al., 2019). Between 1960 and 2004, 121 anomalous mass stranding events were reported; of these, half involved Cuvier's beaked whales and 37 were either strongly correlated in time and space with naval activities, or occurred in naval training areas where US Navy and/or NATO fleets were stationed and operated (D'Amico et al., 2009; Bernaldo de Quiros et al., 2019). Necropsies performed on 10 of the 14 beaked whales stranded in the Canary Islands in 2002 during a NATO naval exercise (with MFAS) revealed disseminated microvascular haemorrhages associated with widespread gas and fat emboli within blood vessels and vital organs, consistent with decompression-like sickness (Jepson et al., 2003; Fernández et al., 2005). Experiments that followed these results highlighted also behavioural responses by beaked whales to simulated and actual mid-frequency sonars. The beaked whales exposed to three sound playbacks at sound pressure levels below 142 dB re 1 μPa stopped echolocating and performed unusually long and slow ascents from their foraging dive (Tyack et al., 2011). During an actual sonar exercise, whales avoided the area of sonar transmission, moving up to 16 km away and returning over 2-3 days only when the sonar exercises ended (Tyack et al., 2011). These types of results were critical because they demonstrated disruption of foraging behaviour and avoidance at exposure levels well below those used by regulators to define disturbance (Tyack et al., 2011; DeRuiter et al., 2013). More recent studies have suggested impacts on local populations of beaked whales from repeated exposure to naval exercises. For example, the population inhabiting the area of the US Navy AUTEC naval range in the Bahamas had lower abundance and recruitment success (calf to female ratio) than other off-range Bahamian populations (Claridge, 2013). In California, Navy activities were suggested as one of the potential causes (along with ecosystem change) of the steep decline in beaked whale populations in the California Current system (Moore and Barlow, 2013).

While beaked whales received much of the research efforts due to their clear sensitivity to naval sonars, a growing body of work reports the evidence of the effects of sonars also on other species of marine mammals and fish. For example, a young male beluga whale (*Delphinapterus leucas*) exposed to mid-frequency sound (19–27 kHz; 140–160 dB re 1 μPa) exhibited significantly increased heart and respiration rate, with the heart rate increasing with the intensity of the sound level (Lyamin et al., 2015). Tagged blue whales (*Balaenoptera musculus*) showed disruption of feeding activity, avoidance and increased swim speed when exposed to a mid-frequency sonar's received levels of 140 dB re 1 μPa (Goldbogen et al., 2013). Sivle et al. (2015) reported that minke whales (*Balenopterus acutorostrata*) exhibited high speed avoidance when exposed to 1–2 kHz sonar signals, with avoidance starting at sound pressure levels of 130 and 146 dB re 1 µPa. Furthermore, minke whales have been reported stranding during several military sonar-related beaked whale mass stranding events (Parsons et al., 2008). Finally, other than beaked whales, several other species have been reported stranding in coincidence with naval exercises: dwarf sperm whales (*Kogia sima*); pygmy sperm whales (*K. breviceps*); short-finned pilot whales (*Globicephala macrorhynchus*); long-finned pilot whales (*G. melas*); pygmy killer whales (*Feresa attenuata*); and several dolphin species (*Stenella attenuata and S. coeruleoalba*) (Parsons, 2017). Bottlenose dolphins (*Tursiops truncatus*) exposed to increasing levels of mid-frequency sonars playbacks showed increasing behavioural disruption, all dolphins within the experiment abandoned trained behaviours at exposures of 185 dB re 1 µPa (Houser et al., 2013b).

Harbour porpoises (*Phocoena phocoena*) may be sensitive to naval activities too. In 2005, 85 harbour porpoises stranded along approximately 100 km of Danish coastline within a week (Wright et al., 2013). The ultimate cause of death for most individuals was bycatch; however, the bycatch coincided with the presence of military vessels aggregating in the area for the largest NATO naval exercise in Danish waters to date. Although sonar usage could not be confirmed in the days leading up to the incident, the timing is noteworthy (Wright et al., 2013). Temporal threshold shifts (TTS) caused by low and mid frequency sonar playbacks have been investigated extensively in harbour porpoise (e.g. Kastelein et al., 2014; Kastelein et al., 2015a). TTS is commonly used to extrapolate the exposure levels required to inflict minimal permanent injury to the hearing organs (PTS), used as a precautionary criterion for injury (Southall et al., 2007; Southall et al., 2019). See (Tougaard et al., 2022) for a recent review.

Dose-response experiments carried out with California sea lions (*Zalophus californianus*) also showed behavioural responses to the exposure of a simulated military mid-frequency sonar (3.25 – 3.45 KHz). The severity of the behavioural response increased directly with sound pressure level, which ranged from 125 to 185 dB re: 1 µPa (rms) (Houser et al., 2013a). In another experiment in captivity, hooded seals (*Cystophora cristata*) responded to a 10% duty cycle exposure with avoidance to signals above 160 to 170 dB re 1 µPa (rms) received levels. The responses included reduced diving activity, commencement of rapid exploratory swimming at surface, and eventually displacement to areas of least sound pressure level. Heart rate increased at the surface indicating emotional activation during sonar exposure; however, during diving the effect of sonar exposure on the heart rate was absent (Kvadsheim et al., 2010). In a similar experiment, with a smaller enclosure, two harbour seals (*Phoca vitulina*) displayed a range of behavioural responses when exposed to 25 KHz sonar signals. These ranged from no reaction to increased time spent at the water surface, numbers of jumps, hauling out, and increased swimming speed. Results suggested that frequency modulated sonar signals with SPL above 125 dB re 1 µPa were the main cause of significant behavioural responses (Kastelein et al., 2015b).

Effects of mid-frequency naval sonar on fish have been investigated in a few studies. Rainbow trout exposed in two different studies with low (170 – 320 Hz) and mid-frequency (2.8 – 3.8 kHz) sonars (signal levels: 193 - 210 dB re 1 µPa RMS (Kane et al., 2010); 220 dB re 1 µPa^2 s (SEL_{cum}) (Halvorsen et al., 2012c) showed no exposure-related pathologies concerning the inner ear as well as no impacts on the animals hearing sensitivity. In contrast, Halvorsen et al. (2012c) reported that a test group of channel catfish (*Ictalurus punctatus*) showed a statistically significant TTS of 4–6 dB at 2300 Hz, but not at lower tested frequencies, whereas a second test group showed no change. Similar results were reported also by Halvorsen et al. (2013) who recorded no effects of low-frequency naval sonar exposure for largemouth bass (*Micropterus salmoides*) and yellow perch (*Perca flavescens*) and small hearing threshold shifts (4 dB at 800 Hz and 5 dB at 1600 Hz) up to 24 h after acoustic exposure for channel catfish. The lack of response to both low (1–2 kHz) and mid-frequency (6–7 kHz) naval sonar was also reported in a study conducted in the wild off Northern Norway on schools of Atlantic herring (*Clupea harengus*). The fish schools neither significantly dived nor changed their packing density in response to low and mid-frequency sonar transmissions received by the fish at estimated sound pressure levels (SPLs; RMS) up to 176 and 157 dB re 1 μPa and estimated cumulative sound exposure levels up to 181 and 162 dB re 1 μPa^2 s, respectively (Sivle et al., 2012).

There are three main standard methods to mitigate the potential impacts of naval sonar sound on marine mammals: avoidance of sensitive areas, implementation of operational procedures and maintenance of 'exclusion zones' around the sound source through animal monitoring (Dolman et al., 2009). In general, navies self-regulate and deploy their own mitigation strategies; for more details on how each country implement its own mitigation strategies during naval exercises (Dolman et al., 2009).

2.2.1 Avoidance of sensitive areas

Most naval mitigation guidelines loosely define sensitive areas as breeding, feeding or migration habitat for marine mammals; in addition, some specific measures for beaked whales are usually considered. For example, the waters around the Canary Islands are known to be a favourable habitat for beaked whales, thus a 50 nm exclusion zone is clearly defined and implemented around the Canary Island for Spanish navy vessels (Aguilar and Martín, 2007). Italy and NATO guidelines suggest avoidance of complex seabed topography (canyon, mounts) that beaked whales are likely to inhabit. Furthermore, the Italian Navy imposes a 'buffer' zone of 5 km to keep sonar use outside relevant areas such as whale sanctuaries (Dolman et al., 2009). Another example is the USN National Defence Exemption (NDE), which specifies conditions of heightened risk for beaked whales for mid-frequency active sonar exercises taking place in established ranges. These conditions include rapid bathymetry changes, the use of multiple ships or submarines over extended periods, the presence of channels and bays, and the occurrence of significant surface ducts. It is questionable how many areas would actually meet these narrowly defined criteria, as well as the fact that if these conditions are present, the guidelines suggest only increased vigilance if the military test could not be avoided (Dolman et al., 2009). An interesting tool developed by the Norwegian Defence Research Establishment (FFI) for the Norwegian Navy to aid the planning and operation of sonar exercises is SONATE (Nordlund and Kvadsheim, 2015). SONATE combines cartographic information on historical and current species distribution, fishing activity and fish farms with the guidelines that define the actions to mitigate environmental impact.

Environmental impact assessments/statements (EIAs/EIS) are often a legislative requirement to plan and execute naval exercises that involve active sonars. Even if challenging, EIAs and EIS are instrumental in assessing the cumulative impacts of exercises in particular areas of frequent sonar occurrence. As an example of the ongoing and regular use of a maritime exercise area without (at least until 2009) EIAs and EIS is brought up by Dolman et al. (2009). The Joint Maritime Course (JMC) military training exercise was conducted three times a year in coastal and deep waters to the North and West of Scotland between 1946 and 2006. Military jets, submarines, warships (including minesweepers and sub-hunters), landing craft, power boats and sonobuoys were utilised during these exercises. The authors suggest that an EIA would be beneficial to understand if over a 60 year time period the presence and combination of these activities could have negative impacts on the rich marine fauna of the West coast of Scotland (Dolman et al., 2009).

2.2.2 Implementation of operational procedures

One of the main mitigation measures that is often used during naval exercises that involve active sonars is a ramp-up or soft-start procedure. During a ramp-up procedure, the source level of the sonar is increased gradually at the start of the operation. The rationale is that this gradual increase in source levels would give animals in vicinity of the source the opportunity to move away and therefore minimise the negative effects of a sonar source at full power. Several navies have employed ramp-up procedures in an attempt to mitigate the known effects of military sonars on marine mammal hearing and behaviour. Although the ramp-up procedure is widely adopted, only a few studies have looked at its effectiveness. For example, an experimental study on humpback whales conducted in northern Norway suggested that although in a few instances sonar ramp-up decreased the SPL_{max} and the SEL_{cum} of the signals the whales were exposed to, the overall results indicated that the ramp-up had limited mitigative effects (Wensveen et al., 2017). The authors recorded changes in heading (interpreted as avoidance manoeuvres) in only 50% of the whales exposed to the sonars; therefore, they suggest that ramp-up procedures could be more effective for species more responsive to sonar noise. A similar point was raised in another study (Von Benda-Beckmann et al., 2014) in which the authors modelled the effectiveness of ramp-up simulating the level of sound killer whales (*Orcinus orca*) would be exposed to from a generic sonar operation. The results indicated again that the presence of ramp-up procedures could reduce the risk of killer whales receiving sound of sufficient intensity to cause harm to their hearing. However, the effectiveness of the ramp-up procedure was strongly dependent on the assumed response threshold, the behavioural context, and varied based on ramp-up duration – although beyond 5 min the predicted mitigating effect did not change significantly. Other factors that limited the effectiveness of this mitigation procedure included high source level, rapid moving sonar source, and long periods of silence between sonar transmissions (Von Benda-Beckmann et al., 2014).

2.2.3 Exclusion zones

Exclusion zone procedures are various operational responses to the presence of marine mammals within a pre-determined radius of the sound source. The implementation of real-time mitigation is dependent on the detection of animals within the exclusion zone using visual and/or acoustic methods. Visual monitoring is the primary method of animal detection across all navies. It is obviously dependent on environmental factors such as weather condition or darkness but also the number of marine mammal observers (MMOs), their experience, the regularity of their breaks, their objectivity (crew member or independent third party) and their level of training (Weir and Dolman, 2007). In some regions of the US, aerial surveys are required before, during and after the naval exercises to complement visual monitoring from vessels. Most navies acknowledge also the efficacy of real-time passive acoustic monitoring (PAM) for enhancing detection probability for marine mammals (Dolman et al., 2009). However, despite use of both visual and auditory information in real-time monitoring, the detection success (percent of animals actually present that are detected) can be very low, especially during poor weather and for deep-diving and/or otherwise inconspicuous species, such as beaked whales and porpoises.

The exclusion zone (or 'safety zone') is usually defined as the radius surrounding the sonar source within which real-time mitigation measures are implemented if animals are detected. Exclusion zones vary considerably from navy to navy and can be larger for naval sonar than for seismic surveying, where a 500 m exclusion zone is standard (Dolman et al., 2009). For example, while the Canadian Navy designates an exclusion zone of 1.85 km for baleen whales (and 1 km for all other marine mammals), the Italian Navy indicates 1.5 km for all marine mammals indistinctively. The Royal Australian Navy has the largest designated exclusion zone (3.66 km) while the French Navy, while operating an exclusion zone, does not specify a distance (Dolman et al., 2009). As a general rule, whenever animals are sighted within the exclusion zones the sonar is either power down or shut down, depending on the distance to the vessel.

As of 2009, Dolman et al. (2009) underlined how it was not clear under what circumstances the naval mitigation measures were a requirement under environmental legislation in each region. Mitigation procedures seem to be designed and implemented on an entirely self-regulatory basis by the regional navies. Furthermore, the guidelines are frequently punctuated by clauses such as 'whenever practicable' ensuring a lack of accountability in the case that the suggested mitigation procedures are not deployed. In addition, some of the guidelines are selective to naval activities occurring in national waters only, without taking into consideration the vast majority of the world's oceans which are still open to naval activities without any marine mammal mitigation measures in place (Dolman et al., 2009).

2.3 Seismic Airguns

Airguns towed behind seismic survey vessels used for seabed mapping and hydrocarbon exploration, and produce impulsive, high intensity sounds. Sound source levels of 248–255 dB re 1 $\mu Pa_{o\text{-}p}$ are typical of large-scale seismic arrays (Kavanagh et al., 2019). Most of the energy produced by airguns is concentrated below 200 Hz, although there is considerable amounts of energy above ambient noise also at higher frequencies (Greene Jr. and Richardson, 1988; Harwood and Wilson, 2001; Hermannsen et al., 2015b; Kyhn et al., 2019). Due to their low frequency spectrum, airgun sounds can travel over large distances. In a study conducted in the Atlantic Ocean, airgun sounds could be recorded almost 4000 km from the survey vessel, and at some locations airgun sounds could be recorded more than 80% days/month for more than 12 consecutive months (Nieukirk et al., 2012).

Recently, to address the need for coordinated monitoring and assessment of impulsive noise in the Northeast Atlantic, OSPAR (the Regional Seas Convention for the Northeast Atlantic) commissioned the International Council for the Exploration of the Sea (ICES) to develop and maintain the OSPAR impulsive noise register (link) in 2015, later also joined by HELCOM. The results of this international effort are effective in showing how dominant and ubiquitous seismic airgun activity is compared to other impulsive noise activities such as sonars, pile driving and explosions, see Figure 2.2 (Merchant et al., 2020).

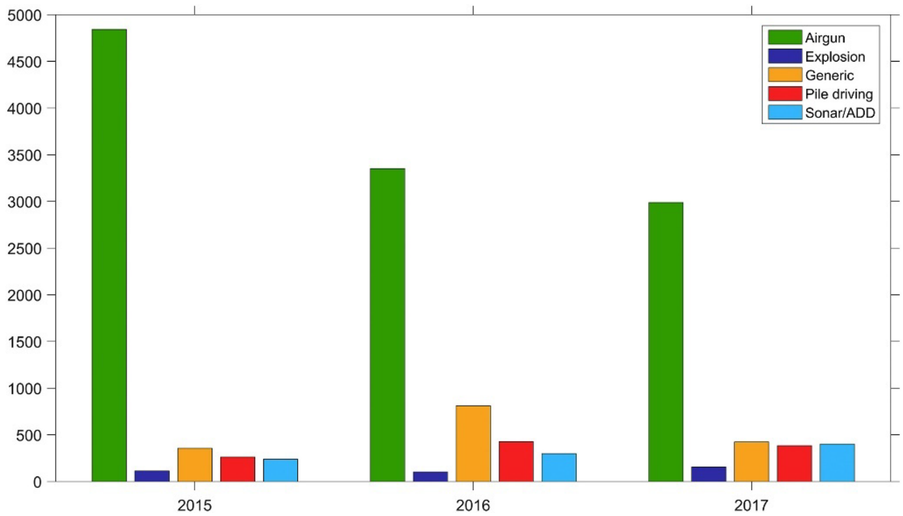

Figure 2.2. Graph taken from Merchant et al. (2020) representing the Overall Pulse Block Day (PBD) by source type for the entire OSPAR Maritime Area during 2015–2017. See Merchant et al. (2020) for details on the methods.

A recent study that modelled over 8000 hours of cetacean survey data across a large marine ecosystem found a significant effect of seismic activity across multiple marine mammal species and habitats. Baleen and toothed whale sightings decreased during active seismic surveys by 88% (82-92%) and 53% (41-63%) respectively, compared to control surveys (Kavanagh et al., 2019). Several studies have confirmed the conclusions of Kavanagh et al. (2019) by providing further evidence of behavioural disruption and spatial avoidance caused by airgun noise exposure, especially in baleen whale species which are presumed to overlap in their hearing with the low frequency bands of airgun noise (Gordon et al., 2003; Di Iorio and Clark, 2010; Castellote et al., 2012; Cerchio et al., 2014; Blackwell et al., 2015; Dunlop et al., 2017).

Odontocetes show avoidance responses to seismic airguns too. For example, harbour porpoises in the North Sea have been monitored acoustically during a seismic survey conducted between July and November 2016. The results showed a decrease in echolocation signals up to 8–12 km from the active airguns; the authors suggest that this might indicate temporary displacement of porpoises or a change in porpoise echolocation behaviour (Sarnocińska et al., 2020). Similar results, but at a much higher spatial scale have been described by van Beest et al. (2018) after exposing tagged harbour porpoises to airgun pulses at ranges of 420–690 m with noise level estimates of 135–147 dB re 1 μPa^2s (SEL). Three of the five individuals tagged displayed either rapid and directed movements away from the airgun location, or disruption of baseline diving behaviour. Complete recovery to natural behaviour occurred after 24h. Temporary displacement of harbour porpoises caused by a seismic survey has been documented also by Thompson et al. (2013) who measured group responses over ranges of 5-10 km at SEL of 145–151 dB re 1 μPa^2s.

Although seals seem to be less sensitive to airgun noise, behavioural disruptions have been recoded. For example, grey seals showed avoidance and switched from foraging to transiting behaviour and increased hauling out after being exposed to a single airgun or small airgun array. Harbour seals exhibited a more dramatic avoidance behaviour, they stop feeding and showed a heart rate decrease (Thompson et al., 1998). A visual survey conducted onboard a seismic vessel off Northern Alaska measured similar seal sighting rates between active and inactive airguns (Harris et al., 2001). However, seals tended to be significantly farther away during full-array seismic activity. Partial avoidance was recorded within 150 m of the seismic vessel, but animals seemed to not move further than 250 m.

Behavioural disruption and avoidance also characterise the response of fish and squid to airgun noise. Captive marine fish and squid exposed to noise levels between 120 and 184 dB re 1 μPa²s (SEL) responded by moving to the bottom of the water column and swimming faster in more tightly cohesive groups as the noise levels increased. Airgun noise levels exceeding 147–151 dB re 1 μPa SEL significantly increased the occurrence of alarm responses in both fish and squid (Fewtrell and McCauley, 2012). In another study, video recordings of fish abundance on a reef revealed that during a seismic survey 7.9 km away, reef-fish abundance declined by 78% in the evening hours when fish habitat use was highest on the previous three days without seismic noise (Paxton et al., 2017). Fish behavioural disruption and avoidance can lead also to reduced catch in fishery. In a study that looked at the effects of seismic surveys on fish abundance, fishing success has been shown to be reduced for at least 5 days after the airgun activity terminated, up to a distance of 33 km from the survey track (Hirst and Rodhouse, 2000). Slabbekoorn et al. (2019) highlighted also that the impact of seismic surveys on fishing catch rates can both be positive or negative depending on the type of fisheries: catch rates can go up for gill nets, which depend on swimming activity, or can go down for longlines, which depend on active foraging. The comprehensive literature review produced by Slabbekoorn et al. (2019) is also important because it underlines current knowledge gaps and the need to investigate more behavioural changes for free-ranging fish caused by seismic surveys, and how these changes affect energy budgets and feeding/mating performances. Furthermore, the authors provide a conceptual framework for upscaling individual impacts to the population, community and ecosystem level through experimental and theoretical approaches.

To reduce the risk of potential impacts, licensees involved in offshore seismic surveys are often required to carry out an Environmental Impact Assessment (EIA), to plan accordingly their operations and to monitor during the survey the presence of marine mammals and other potentially sensitive species, so that mitigation actions can be taken. The purpose of the EIAs is to describe the activity, outline the regulatory framework and requirements, identify the environmental aspects, assess the single and cumulative environmental impacts, provide a plan to mitigate the identified risks, and finally assess if the residual risk is acceptable (Bröker, 2019). Some of the aspects that should be taken into consideration during planning stage are to use the lowest practicable power levels to achieve the geophysical objectives of the survey, seek methods to reduce unnecessary high frequency noise produced by the airguns. Furthermore, available animal distribution data should be obtained, such that the marine mammal/fish species likely to be present during the survey are known, allowing the survey to be planned to avoid periods of high animal density (Kyhn et al., 2011a; JNCC, 2017). Finally, possible cumulative effects caused by other seismic operations in nearby licensing areas should be considered (Kyhn et al., 2011b).

During the survey the potential impacts of airguns sounds on marine mammals are categorised by decreasing severity: mortality, injury, PTS/TTS, behavioural disturbance and communication masking. With decreasing received sound levels and impact severity, the concentric regions around the sound source increase in surface area (see Figure 2.3). However, the sound propagation properties of water means that the ranges at which masking and behavioural responses are likely to occur are often orders of magnitudes larger than the ranges where TTS and PTS is likely to occur (Tyack and Thomas, 2019).

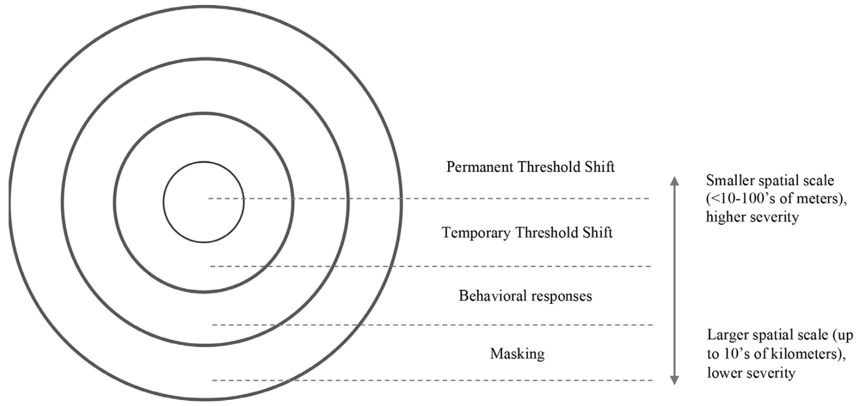

Figure 2.3. Image taken from Bröker (2019) outlining the concentric regions around the sound source that correspond to the different severity levels of impact.

The efficacy of visual monitoring by Marine Mammal Observers (MMOs) is dependent on daylight hours, good weather conditions and animal behaviour. Current guidelines prescribe also the use of passive acoustic monitoring (PAM) to overcome the limitations of visual observation (Kyhn et al., 2011b; JNCC, 2017). PAM detects an animal's vocalisations using hydrophones, monitored by human observers and/or using acoustic analysis software, such as PAMGuard software (www.pamguard.org; Gillespie et al., 2008), to detect, classify and localise marine mammal vocalisations in real-time. Additional promising approaches that could potentially enhance the detection of marine mammals in low visibility conditions include active acoustic monitoring (sonar), thermal imaging (thermal IR) and radar. See Verfuss et al. (2018) for evaluation of the currently available monitoring systems for seismic surveys. They conclude, that as there is no single monitoring system that can provide high detection probability over a wide range of species and environmental conditions, the combination of two or more monitoring systems employing different and complimentary methods is undoubtedly the most effective way to increase the overall detection efficiency and conduct monitoring and mitigation during seismic surveys.

2.4 Underwater explosions

Underwater explosions are used in a variety of contexts such as seismic surveys (albeit rarely), construction and demolition, coastal developments, naval exercises, fishing and removal of unexploded ordnances (UXOs). Underwater explosions generate a series of pressure pulses, after-flows of water and bubble waves in the water column which can cause disturbance, injury, or even death, to marine mammals and other marine species at considerable distances from the source (Harwood and Wilson, 2001). Impact from explosions come in two types: blast trauma to tissue, especially in connection to air-filled cavities such as lungs and intestines (Lance and Bass, 2015; Lance et al., 2015); and auditory trauma, where the middle ear and/or inner ear is damaged.

2.4.1 Blast trauma

Tissue damage due to blast trauma occurs because of differential acceleration of tissues with different densities and compression followed by inflation of air-filled pockets in lungs (swimbladders for fish), intestines, and middle ear and associated sinuses, caused by the high overpressure quickly followed by rarefaction on the shock wave. Ketten et al. (1993) examined the temporal bones from two humpback whales, which died following a 5000 kg charge explosion in Trinity Bay, Newfoundland. Evidence of mechanical trauma consistent with a blast injury was found in all four ears. Experiments with monkeys, sheep and dogs formed the basis for defining a safe limit for marine mammals of 35 kPa · ms (expressed as the acoustic impulse) (Yelverton et al., 1973), later adjusted to 30 kPa · ms based on a review of human injuries and fatalities caused by underwater explosions (Lance et al., 2015). These thresholds are exceeded within distances of several kilometres of larger explosions, such as clearing of UXOs, indicating significant risk of injury or even death within this zone around the blast site. See also von Benda-Beckmann et al. (2015).

2.4.2 Acoustic trauma

Substantial effort has been directed at defining criteria and establishing thresholds for onset of acoustic trauma in marine mammals. This work resulted in the first comprehensive review by Southall et al. (2007), where minimal permanent threshold shift (PTS) is recommended as criterion for injury and exposure limits established by extrapolation from thresholds for onset of temporary threshold shift (TTS) in marine mammals. TTS can and has been measured experimentally in a wide range of marine mammals (Finneran, 2015). Thresholds have recently been updated (Southall et al., 2019) and are expressed as a dual criterion, consisting of a cumulated sound exposure level and a peak pressure, whichever is exceeded first. Pairs of sound pressure levels and peak pressures have been established for seven different functional hearing groups of marine mammals, each with a group-specific auditory frequency weighting function (Southall et al., 2019).

2.4.3 Mitigation

Mitigation could entail precautionary safety distances as seen in the previous study, or methods to decrease the transmission of acoustic energy, like air bubble curtains. After World War II large amounts of ammunitions, including mines and chemical weapons were dumped into the Baltic and North Sea. Following the plan to remove and detonate more than 100 mines and warheads 2.5 km off the coast of North Germany, Sundermeyer et al. (2012) investigated the efficacy of air bubble curtains using test charges. The test area is a well-known harbour porpoise habitat, and porpoises are found in the area all year round. Results on the acoustic presence of harbour porpoises in the area suggested that detonation of test charges in April and June 2008 led to a prolonged absence of porpoises. Furthermore, porpoises avoided the test site over a range of 10 km for 12 h after detonation. The use of air bubble curtains, set in three different configurations, led to a reduction in peak sound pressure level between 11.1 and 17.3 dB re 1 µPa. The authors of the study concluded that the detonation of sea mines and warhead, with charges up to 350 kg (much larger than the test charges), should be avoided unless animals can be effectively excluded from the risk zone and effective mitigation procedures could be employed to reduce the emitted sound levels (Sundermeyer et al., 2012). Schmidtke et al. (Schmidtke et al., 2009; Schmidtke, 2011) also studied the efficacy of an air bubble curtain to attenuate the shock wave from detonation of WW2 sea mines and showed that it was possible to reduce peak levels with a functional bubble curtain.

More recently, (Siebert et al., 2022) documented severe tissue injuries in stranded porpoises, many likely fatal, following a major UXO clearing campaign in the Western Baltic, further highlighting the significance of the impact.

Promising alternatives to detonating UXOs in place include various types of chemical disintegration or slow burning of the explosives (deflagration, or low-order detonation). This can be accomplished in ways that greatly reduce the peak pressure (Robinson et al., 2020) and thereby greatly reduce or even eliminate the risk of tissue damage and acoustic trauma.

3 Actions directed at continuous noise

Marine traffic in the world's oceans has increased steadily in the last century. Between World War II and 2008 the global number of ships increased by a factor of 3.5 while the gross tonnage increased by a factor of 10 (Frisk, 2012). This increase in marine traffic altered the soundscape of the oceans, which was until then dominated by sound from natural sources (biological and geophysical). In a study conducted in the North East Pacific, and potentially indicative of other regions, it was estimated that since the 60s, low frequency continuous noise (dominated usually by shipping noise) in deep water has increased with 3 dB per decade (Andrew et al., 2002; McDonald et al., 2006). In addition, recent model projections taking into account economic trends suggest that this increase in noise will continue to grow by a factor of 1.9 by 2030 (Kaplan and Solomon, 2016).

3.1 Effects of continuous noise

The concern for the effect of shipping noise on marine wildlife is not new, but dates back to the early 1970s (Payne and Webb, 1971; see recent review by Erbe et al., 2019). Recent research into this field in the last couple of decades have made policy makers and stakeholders acknowledge the problem (e.g. NMFS, 2018) and work towards mitigation solutions (e.g. IMO, 2014). Although there are significant knowledge gaps, it is now well accepted that increasing shipping noise levels are detrimental for marine species that rely on sound. Noise from shipping can alter the behaviour, mask reception of other sounds, as well as cause physiological effects (Wright et al., 2007).

The shipping routes found in the Baltic Sea are used by about 2000 ships at any given moment and about 3,500–5,500 ships navigate through the Baltic Sea per month. More than 50% of the ships are general cargo ships. Approximately 20% of the ships in the Baltic Sea are tankers carrying in total over 200 Mio. tons of oil, about 11% are passenger ships carrying about 50 million passengers (Matczak, 2018). This high density of human activities poses potential problems regarding the impact of noise on both marine mammals and fish species inhabiting the Baltic waters.

3.1.1 Masking of detection and communication

Depending on its hearing abilities, an animal can detect a sound source against the ambient noise, if its hearing is more sensitive than the ambient noise under prevailing conditions, as is most commonly the case for mammals within their frequency range of best hearing. An increase in ambient noise will however lead to deterioration, or masking, of the perception of sound by the animal (Erbe et al., 2016). Masking occurs naturally in the marine environment, as wind, waves and other animals (conspecifics and other species) elevate the ambient noise. However, in the presence of anthropogenic noise, such as ship noise, masking can drastically reduce the detection range of animal signals. Masking is perhaps the most pervasive way in which continuous noise affects the life of marine mammals and fish (Erbe et al., 2016). Masking is defined as the process by which the ability to detect or recognise a sound is degraded by the presence of a 'masker' sound. From a quantitative point of view, masking refers to the amount of dB by which an auditory detection threshold is raised in the presence of a masker sound (American National Standards Institute, 2013).

Marine mammals and fish rely heavily on acoustic signals during their life cycles. Within the Baltic ecosystem, acoustic signals are used in a variety of contexts, including navigation, sexual display and mother-calf communication in harbour porpoises (Clausen et al., 2010), courtship in seals (Van Parijs, 2003; Van Parijs et al., 2003), spawning and school coherence in cod and herring respectively (Hawkins and Rasmussen, 1978; Wilson et al., 2004). Most of the energy in ship noise is emitted at low frequencies (centred in the 20-200 Hz band; Tyack, 2008) with the potential to mask signals produced by seals and fish. In addition, high-frequency components are also present in ship noise (up to 160 kHz at short distances ≈ 1 km) and should be considered when estimating potential masking effects for harbour porpoises (Hermannsen et al., 2014).

Several compensatory mechanisms are available to animals to alleviate the effects of masking. 1) Increasing the signal amplitude is a way of enhancing the signal-to-noise ratio of vocalisations and to stand out over background noise, this is also known as Lombard effect (Lombard, 1911). 2) The second compensation strategy to respond to band-limited noise involves changing the frequencies (and their modulation) of vocalizations to shift away from the frequency band in which noise is concentrated. 3) Increasing repetition rate and call redundancy increases the probability of being detected by a conspecific and reduces the potential for masking. However, these compensatory mechanisms only serve to increase the range of useful signal to noise rations in which communication can occur reliably. Ultimately, under given ambient noise conditions (whether purely natural or with smaller or larger anthropogenic contributions) and sound propagation conditions, there is a maximum range, beyond which communication between individuals of a given species is no longer possible. If ambient noise is further increased, for example by a passing vessel, this maximum communication range must decrease. The conclusion is that adding more noise to a soundscape where one or more species are noise-limited in their communication range *must* lead to a reduction in the maximum communication range.

3.1.2 Effects on behaviour

Effects of continuous noise, such as ship noise, on fish and marine mammal behaviour is extremely variable, ranging from freezing, over avoidance to outright flight responses. No matter what the response is, however, the inevitable result is that less time can be spent on whatever the animal was doing at the time of disturbance. A second consequence of this loss of opportunities for feeding, sleeping, nursing offspring or mating, is that many small disturbances accumulate over time. Disturbance thus inevitably means less food intake, less rest and sometimes increased energy expenditure, due to evasive behaviours – all, which contribute to an overall loss of fitness to the animal. However, measuring and quantifying behavioural changes and in particular the energetic consequences, in marine animals is logistically complicated and moreover, complicated by the fact that animal responses are strongly context-specific, with variables such as age, behavioural state (foraging, nursing etc), sex, life history as well as acoustic characteristics of noise all mediating the response to noise (Southall et al., 2021). Linking short term behavioural responses to long term impacts at individual and population level remains one of the greatest challenges of this research field (HELCOM, 2019).

Observations during abundance studies using transects have shown that harbour porpoises react to ships at moderate distances from the ship (800–1000 m; Barlow, 1988; Palka and Hammond, 2001; Bas et al., 2017) probably triggered by the noise of the research vessels. More recently, dedicated sound exposure experiments showed harbour porpoises reacting strongly to medium and high frequency components (above 2 kHz) of shipping noise at relatively low amplitudes (Dyndo et al., 2015). The most recent study that looked at the effects of ship noise on harbour porpoises showed that tagged individuals encountered ship noise 17-89% of the time (16 kHz third-octave; Wisniewska et al., 2018). Furthermore, high-noise level events coincided with vigorous fluking, bottom diving, interrupted foraging and cessation of echolocation. This lead to significantly fewer prey capture attempts at received noise levels greater than 96 dB re 1 μPa (16 kHz third-octave; Wisniewska et al., 2018). Considering the high metabolic rate harbour porpoises need to maintain to survive in the cold Baltic waters, foraging disruption caused by shipping noise might entail negative short- and long-term fitness consequences (Wisniewska et al., 2016).

The effects of shipping noise on seal behaviour have not been documented comprehensively. Terhune et al. (1979) measured a marked decrease in harp seal (*Pagophilus groenlandicus*) vocalizations when vessels were transiting in the study area. Tripovich et al. (2012) documented avoidance behaviour and increased aggression of Australian fur seals (*Arctocephalus pusillus*) at a haul-out site to high amplitude playbacks of shipping noise. In a different study, the presence of vessels negatively impacted the probability of harbour seals to be hauled out; in addition, large-sized tourism vessels were significant predictors of ending haul-out bouts (Blundell and Pendleton, 2015). Similarly, grey seals appear to have been displaced by high levels of vessel traffic during the construction of an underwater gas pipeline through a bay on the north-west coast of Ireland, most likely due to ship noise disturbance (Anderwald et al., 2013).

3.1.3 Physiological stress responses

Physiological stress caused by ship noise has been documented only a handful of times in marine mammals due to the difficult logistics of designing controlled experiments. In captivity, belugas exposed to anthropogenic noise showed a significant increase in heart rate (Lyamin et al., 2015). In the wild, Rolland et al. (2012) documented a decrease in baseline levels of stress-related faecal hormone metabolites (glucocorticoids) of North Atlantic right whales (*Eubalaena glacialis*) in conjunction with an underwater noise decrease of 6 dB (with a significant reduction under 150 Hz) caused by reduced ship traffic following the events of 11 September 2001.

In multiple fish studies, exposure to ship noise has shown to trigger an increase in hormones (e.g. cortisol) which are usually associated with stress responses (Smith et al., 2004; Wysocki et al., 2006; Anderson et al., 2011). In addition, ample evidence in multiple species suggests that ship noise can also disrupt embryogenesis and larval development by increasing embryos heart rate, reducing yolk size at hatching time, and introducing larval malformations and growth delays (Morgan et al., 1999; Davidson et al., 2009; de Soto et al., 2013; Nedelec et al., 2015; Sierra-Flores et al., 2015; Fakan and McCormick, 2019). However, in most cases of studies on fish and fish larvae, the stimulus is poorly characterized, as only the pressure part of the sound field was measured. The particle motion part of the sound field, which fish, in contrast to mammals, are known to be highly sensitive to (Sand and Enger, 1973; Sand and Karlsen, 2000), were thus ignored.

3.2 Operational solutions to minimise cavitation noise:

Most of the global transportation is carried out by cargo vessels (container ships, oil and gas tankers, bulk carriers, general cargo ships, car carriers etc.). Minimization of cost of transport is the major design criterion for these ships and because there is an inverse relationship between efficiency of the propeller and amount of cavitation (up to a certain point, where cavitation becomes detrimental), some propeller noise resulting from cavitation is accepted for the sake of fuel efficiency as long the propellers are not damaged and the crew does not experience excessive discomfort due to noise or vibration (AQUO, 2015).

Cavitation, which is the formation of bubbles in a liquid when the pressure reaches the vapor pressure and noise is generated at the collapse of these bubbles, represents the dominant source of noise resulting from commercial ship traffic. Cavitation can take various forms and originate in various structures connected to the propeller, including propeller blades, propeller hub as well as hull appendages. An important point made by Spence and Fischer (2017) is that cavitation can be reduced efficiently through propeller design, but that successful propeller designs are not universal. The propeller design needs to be developed for the specific wake profile of the vessel in question.

3.2.1 Regular propeller/hull maintenance:

Regular propeller and hull cleaning represent fundamental practices to maintain the fuel efficiency of a vessel. Furthermore, these practices implicitly reduce the radiated noise too because by decreasing the frictional resistance of the hull/propeller caused by biofouling, the same vessel speed could be attained using less propulsion power, thereby reducing load on propeller and hence less cavitation (IMO, 2014; AQUO, 2015). Propeller/hull cleaning should be performed periodically while the vessel is dry-docked, and in conjunction with the application of antifouling coatings. A 5 % increase in speed due to maintenance could result in a radiated noise reduction of 1-2 dB (AQUO, 2015). The advantage of this measure is that it is fully applicable to any ship, making it a simple and effective solution for maintaining optimal fuel costs as well as reducing radiated noise (Hilliard et al., 2014; IMO, 2014; AQUO, 2015; Hemmera Envirochem, 2016).

3.2.2 Vessel speed and routing control

When it comes to vessel traffic control, no solution can be 'one size fits all' as each geographical area is characterised by a unique combination of ship traffic dynamics, environmental parameters and marine wildlife. Noise mapping tools and simulations are extremely important to develop relevant, site-specific traffic control scenarios that could be presented to stakeholders, in order to deploy effective noise mitigation measures. There are three potential mitigation measures that could be implemented at the level of the control of ship traffic: introduction of speed limits, marine spatial planning, and application of noise labels (AQUO, 2015).

The amount of cavitation created by a ships propeller and, consequently, the amount of noise radiated from the ship, is strongly dependent on the speed of the vessel and generally monotonically increasing above the cavitation inception speed (AQUO, 2015). However, vessels with controllable pitch propellers (CPP) operated at high revolution rates can emit high underwater noise even at low speeds (AQUO, 2015), leading to non-monotonic relationships between speed and noise. Setting regional or local speed limits, either absolute (in knots) or relative (percent of designed service speed) would help lowering the amount of noise radiated by fixed pitch propeller ships. Such a reduction, however, must be counterbalanced by the increased transit time, leading to an increase in cost for a commercial operator for moving more slowly, but also the reduced fuel consumption per travelled distance (cost of transportation) must be factored in.

The recent Enhancing Cetacean Habitat and Observation (ECHO, 2019) program led by the Vancouver Fraser Port Authority conducted a vessel slowdown research trial in Haro Strait, a key summer feeding area for the southern resident killer whale (*Orcinus orca*) population. This voluntary slowdown trial demonstrated that reducing vessel speeds can be an effective measure to decrease underwater noise generated by ships and its impact on the surrounding soundscape. The speed limits were set at 15 knots or less for vehicle carriers, cruise and container vessels and at 12.5 knots or less for bulkers, tankers, Washington State Ferries and government vessels. Voluntary participation has been high (87 %) and 77% of all transits fell within 1 knot of the target speed limits. Results from 2017-2018 trials indicated a median reduction of broadband received sound pressure level (SPL) of 1.5-1.7 dB. Furthermore, noise modelling predicted a reduction between 15-22 % of affected foraging time on an average traffic day due to the slowdown, potentially improving foraging conditions for this killer whale population (ECHO, 2019). Although the specific set up of the ECHO program cannot be transferred directly to other geographical areas, the important lesson that can be taken away is that that coordinating a voluntary ship slowdown for commercial ships outside port authority's jurisdiction is complex, and it involves collaboration with many stakeholders (federal agencies, shipping associations, ship agents and operators, pilots and researchers).

AQUO (2015) lists several potential spatial panning measures that could be applied to reduce radiated noise. Ship traffic can be concentrated, similar to Traffic Separation Schemes (TSS) to concentrate ship traffic to prescribed routes that would guide vessels away from noise sensitive areas. On the other hand, ship traffic could also be spread out (diluted). This measure would aim at homogenising traffic density, in order to avoid high intensity noise hotspots. Similarly, separation between single vessels along the shipping lane could lead to the same result. Another possibility is to form ship convoys, grouping several ships based on their speed capabilities and noise radiation characteristics could help by masking the noise radiated by the quieter ships by the louder ones. This will ultimately lead in a spatial/temporal reduction of noise exposure across the marine area of concern. In the end, the management objective must be clear, before decisions on which scheme(s) to select. More specifically: is the aim to reduce the occurrence of high-intensity events in identified hotspots for marine life, in which case re-routing and dilution is the answer. Or is the aim to reduce the average exposure to more evenly dispersed marine life, in which case concentration and convoying is the answer.

A fifth possible measure when planning marine traffic is to exploit bathymetry features across the area of interest. Due to absorption of sound waves in the sea bottom and reflection in the water surface respectively, low frequency sound propagate poorly in shallow waters, as opposed to deep waters where it can travel long distances. Moreover, natural features such as underwater canyons or islands can help confine or block underwater noise. Therefore, the geographical features and bathymetry of an area should always be considered when planning ship traffic routes; for example, by establishing TSS above and along underwater canyons and shallow waters or by using islands to block ship traffic noise across an area of concern.

Finally, ships could be categorised based on the amount of noise they produce (AQUO, 2015) in a classification system. This could help regulate or prohibit the access to sensitive areas if underwater radiated noise from a given ship exceeds a set noise level, specific for the sensitive area. During the last few years, several ship classification societies have developed environmental certification programs in which shipbuilders and operators can voluntarily enrol into to measure and reduce radiated noise from their individual ships. Non-government organisations such as Bureau Veritas, DNV GL, RINA, and Green Marine are responsible for establishing, maintaining and inspecting to technical standards for the construction and operation of vessels. These certification programs are important because they leave more flexibility to the ship operator by which means the required reduction of single vessel radiated noise is achieved. Furthermore, certification metrics can be used within incentive-based policies and programs. An example of this is the EcoAction Program developed by the Vancouver Fraser Port Authority. This program, launched in 2007, offers discounts (up to 47 % off) on harbour dues to vessels meeting voluntary environmental best practices (certified by the above mentioned organisations) that reduce emissions, underwater noise and other environmental impacts (Hemmera Envirochem, 2016).

3.3 Technical Solutions to reducing ship noise

As a supplement to operational measures to reduce underwater noise from ships, there are numerous technical solutions to reducing radiated noise. All of these, however, ultimately face an unfavourable trade-off between propeller efficiency (and hence fuel use) and radiated noise, beyond some optimal point, specific for the given propeller design and vessel type. This means that a ship cannot be designed to have an arbitrarily low noise profile without an associated increase in fuel use (cost of transportation).

3.3.1 Coating of propeller surface

Anti-fouling coating have been used for many years in the marine industries; applied on the ship hull they prevent fouling that increases the frictional resistance of the hull. This is true also for propeller coating, that has been reported to increase a propeller efficiency by 6%, compared to an uncoated propeller (Atlar et al., 2002). It has been demonstrated that propeller coating can also influence cavitation. Bagheri et al. (2017) tested an Intersleek 700 coating of 200 µm thickness on a 5-blade propeller inside a cavitation tunnel. Their results indicated that propeller coating could prevent cavitation inception resulting in a noise decrease of 2-4 dB at frequencies lower than 1 KHz, compared to an uncoated propeller tested in the same conditions.

3.3.2 High skew propellers

An option to decrease cavitation is to modify the skew of the blade, which makes the blade curve in the direction of the water flow (Smith and Slater, 1988). High skew propellers receive lowers blade-rate pressures, leading to decreased ship vibrations and reduced cavitation (Renilson Marine Consulting Pty, 2009; Spence and Fischer, 2017). This type of propeller design is commonly used in warships and high-powered merchant ships to reduce their noise output and vibration (Renilson Marine Consulting Pty, 2009). The use of high skew propellers is thought to decrease irradiated noise by up to 10 dB, and increase the propeller's cavitation inception speed by up to 2 knots (Hilliard et al., 2014).

3.3.3 Contracted and loaded tip (CLT)

Noise reduction can be attained also by implementing modern propeller designs, developed specifically to increase propeller efficiency and decrease noise output. An example of these types of propellers is the CLT propeller, in which each blade tip features a backward or perpendicular plate. This plate acts as a barrier between the back and front of the blade resulting in a decrease of water flow between the high- and low-pressure sides of the blade leading to an increase in propeller efficiency between 5-8% (Meccanica, 2014; Ebrahimi et al., 2019). For this specific design, in CLT propellers the probability of cavitation is less than in conventional designs, therefore decreasing the irradiated noise. They are produced by the Spanish company SISTEMAR and they have been deployed already on more than 280 vessels of various type (Gonzalez- Adalid et al., 2006; Renilson Marine Consulting Pty, 2009; Gennaro and Gonzalez- Adalid, 2012; Meccanica, 2014).

3.3.4 Kappel propellers

In this propeller design the blade tips are smoothly curved towards their suction side. The first full-scale Kappel propeller was deployed in 2002 on a product carrier showing a 4% increase in propeller efficiency compared to conventional propellers (Andersen et al., 2005). Furthermore, in a study on the application of Kappel propellers to submarines, Andersen et al. (2009) tested in a three stage development process 8 different configurations of Kappel propellers that varied in number of blades (7 or 8) and geometric configurations. The results suggested that propellers with an even number of blades (8 in this case) could reach a substantial noise reduction of more than 10 dB (at frequencies around 100 Hz) compared to a propeller with an odd number of blades (7, in the study).

3.3.5 New blade section (NBS) propellers

The New Blade Section (NBS) propeller has been developed by Sumitomo Heavy Industries Marine & Engineering Co., Ltd and is referred as a highly efficient propeller, with smaller diameter and better cavitation performance compared to conventional propellers (Sasaki and Patience, 2005; Renilson Marine Consulting Pty, 2009).

3.3.6 New Profile Technology (NPT) propellers

This propeller design has been developed by Stone Marine Propulsion (SMP) Ltd and is characterised by a smaller optimum diameter, lighter weight, and higher efficiency compared to conventional designs. The underwater noise radiation reduction of the NPT propellers measured on a medium-size research vessel was considerable reaching for frequencies over 100 Hz reductions in the order of 10-20 dB (Carchen et al., 2015).

3.3.7 PressurePores

A recent retrofit solution developed to reduce propeller cavitation is represented by the PressurePores™ technology, developed by the UK based Oscar Propulsion company (Aktas et al., 2020). This solution involves the drilling of strategically located pressure-relieving holes across the propeller blades to decrease the amount of tip-vortex cavitation. The authors report a decrease of cavitation noise up to 17 dB with a 2% reduction in propeller efficiency.

3.3.8 Controllable pitch propellers (CPP)

Propeller blade's angles can be fixed (fixed pitch) or adjustable (controllable pitch propeller, CPP); both options have pros and cons but when a CPP is implemented with a variable speed diesel or electric engine propeller cavitation is reduced (Spence, 2007). This cavitation reduction originates from an improved blade angle in relation to specific vessel speed and RPM.

3.3.9 Propeller hub modifications

Propellers' hubs tend to generate vortices; these vortices reduce efficiency and are usually prone to cavitation and, consequently, are an important component of the propeller irradiated noise (Renilson Marine Consulting Pty, 2009). Propeller Boss Cap Fins (PBCF) consists of small fins attached to the propeller hub. They have been designed in Japan and they are effective in decreasing the magnitude of hub's vortices and, consequently, reducing cavitation (Ouchi et al., 1991; Sun et al., 2016). PBCFs are considered a practical solution to reduce noise due to their easy installation, which takes an estimate of 5 hours while dry docked (Renilson Marine Consulting Pty, 2009; Hemmera Envirochem, 2016). Several studies confirm that the implementation of PBCFs leads to an increment of 2-6 % in propeller efficiency, a 4% reduction in fuel consumption, and 3-6 dB reduction in propeller irradiated noise (Ouchi et al., 1991; Ouchi and Tamashima, 1992; Mewis and Hollenbach, 2006; Hansen et al., 2011; Ma et al., 2014; Sun et al., 2016). More specifically, Gassmann et al. (2017) measured irradiated noise from five MAERSK G-class vessels before and after being retrofitted with PBCF. The authors estimated a median reduction of 6 dB in the low-frequency band (8 - 100 Hz) and a median reduction of 8 dB in the high-frequency band (100 - 1000 Hz) after the vessels have been retrofitted. However, the effect of retrofitting confounds with other changes to the ships operation, most importantly an increase in draft, which means the propeller depth is lower. This has additional effects on sound radiation, which were not accounted for (Christ de Jong, pers. comm.).

3.3.10 Costa Propulsion Bulb (CPB)

The interaction between the propeller and the rudder has a significant effect on the efficiency of propulsion. Various designs like the twisted rudder and the rudder fins have been shown to increase efficiency but their effect on irradiated noise has not been confirmed yet (Hemmera Envirochem, 2016). However, a solution that seem to be effective for noise abatement is the Costa propulsion bulb (CPB). This design features a propeller and a rudder integrated hydrodynamically by fitting a bulb to the rudder in line with the propeller shaft (Leaper et al., 2014). This solution eliminates the hub cavitation vortex and is stated that can decrease noise levels by 5 dB (Ligtelijn, 2007).

3.3.11 Wake inflow devices

The water flow in which propellers operate behind the ship is non-uniform. Vessel designers usually need to strike a balance between delivering to the propeller a uniform flow while attempting to have a full hull design to increase the vessel carrying capacity. Wake inflow devices can help by improving the uniformity of the water flow into the propeller leading to reduced cavitation (Renilson Marine Consulting Pty, 2009; Leaper et al., 2014).

3.3.12 Mewis duct

The Mewis duct is designed by Becker Marine Systems and its objective is to improve the flow into the propeller. Feizi Chekab et al. (2014) tested this type of duct in conjunction with propellers with different numbers of blades. Their results indicated that when a 5-blade propeller was implemented in conjunction with the Mewis duct cavitation and thrust fluctuation decreased, which led to a consistent noise reduction (Ebrahimi et al., 2019).

3.3.13 Schneekluth duct

This type of duct was designed to equalise the upstream flow towards the propeller leading to reduced cavitation and noise. While the reduction in noise has not been documented or tested in detail so far, it has been shown that the employment of this duct leads to a 12% reduction in fuel consumption and up to a 50% decrease in vibration (Feizi Chekab et al., 2013).

3.3.14 Twisted rudder

Convectional rudders are subject to uneven forces down their length as a result of the rotation vortex produced by the propeller. The twisted rudder has an altered angle of attack that points into the vortex, this allows the rudder to generate additional thrust as opposed to drag. Moreover, cavitation across the rudder tends to decrease. The manufacturer of this design, Becker Marine Systems, claims that its twisted rudders reduce cavitation noise, however, no concrete evidence is provided (Mappress, 2014). A previous study by Ahn et al. (2012) tested the twisted rudder efficacy on two container carriers showing an improvement in cavitation performance.

3.3.15 Air injection to propeller and bubble curtains

A potential solution described in AQUO (2015) to decrease the amount of propeller cavitation is to inject air upstream of the propeller. This design features a hydrodynamically designed ring with injection holes at the trailing edge equally spaced around the propeller circumference. Results indicated a significant reduction in radiated noise in the order of 10-15 dB in the frequency range 40 - 400 Hz. The reduction of propulsive efficiency correlated with the use of air injection is only 0.5 %; furthermore, the power demand for air compression is practically negligible. However, overall efficiency decreases by 2-3 % due to the drag from the addition of the upstream ring. This inconvenience could be addressed by combining air injection with methods to improve wake, which would lead to both a reduction of radiated noise and an increased fuel efficiency.

AQUO (2015) also investigated another solution to decrease the amount of commercial vessel radiated noise by producing a bubble curtain to isolate the propeller and the hull from the surrounding fluid. Bubble curtains are conventionally used by naval vessels to decrease their acoustic detectability. For a generic cargo vessel at 14 kn, AQUO (2015) researchers estimated a potential reduction of radiated noise between 3 - 6 dB, depending on the frequency range. This solution could be both applied for new designs as well as for retrofits. However, this solution could be less attractive for commercial vessels as it requires additional maintenance.

3.3.16 Machinery noise

Machinery induced underwater noise is usually generated by the vibrations produced by the machinery/engine structures, propagating through the hull structure and into the water. Effective mitigation measures to reduce machinery noise usually consist of decreasing the strength of the noise source (engine type) or by isolating the noise source from the ship hull (elastic mounting, dampening).

Slow speed (2-stroke) engines are used in the vast majority of commercial vessels, especially on long trans-continental routes, due to their high fuel-efficiency. Due to their large weight and power, slow speed engines need to be directly bolted to their foundation ('hard-mounted'); therefore, the use of elastic mounting is not a feasible option.

Medium speed (4-stroke) diesel engines can be mounted elastically, which makes them a great option to reduce underwater noise. Elastic mountings can reduce their noise output by 10 dB at low frequencies and 20 dB at high frequencies (AQUO, 2015). However, compared to slow speed engines, medium speed engines have a higher operational cost over trans-continental routes. Nonetheless, for smaller vessels operating on intra-European routes this type of engine in combination with CP propellers could be an optimal option to consider (AQUO, 2015; Hemmera Envirochem, 2016).

High speed (4-strokes) engines are typically used for special ship types such as High-Speed Crafts (HSC), pleasure boats or smaller naval and offshore supply vessels. These engines tend to emit low machinery noise as they are usually mounted elastically and characterised by very compact housings. However, they are not a feasible option for commercial ships due to their high cost, low fuel-efficiency and limited available powers (AQUO, 2015).

Steam/gas engines are a very effective option to reduce machinery noise due to their low structure borne noise levels and due to the fact they can be better isolated than diesel engines. AQUO (2015) reports that their drawback is the low fuel-efficiency compared to diesel engines, which does not make them a feasible option for commercial vessels. However, a consortium of companies (GTT, CMA CGM and its subsidiary CMA Ships and DNV GL) released a technical and feasibility study for a Liquified Natural Gas (LNG) fuelled, gas and steam turbine powered, and electrically driven container vessels (Würsig and Adams, 2015). This solution would offer a more efficient, more flexible and greener box ship design compared to the current 20,000 Twenty-foot Equivalent Units (TEU) slow speed diesel engines used in ultra large container vessels.

Diesel-Electric propulsion is a hybrid form of propulsion used commonly on cruise liners and research vessels. It utilizes diesel engines to power electric generators which are connected to electric motors that drive the shaft and propeller. Diesel-electric propulsion is significantly quieter than slow speed diesel engine and has the added advantage of being able to be elastically mounted further reducing the vibrations. However, the cost of a diesel-electric engine is prohibitive for commercial vessels and it necessitates clean fuels, which makes it an unrealistic choice for the majority of commercial vessels (AQUO, 2015).

4 Actions directed at other noise sources

The current indicators of the HELCOM monitoring program related to underwater noise, as well as the criteria of the MSFD does not cover all noise sources that could potentially affect marine life detrimentally. There is thus a need for continuous research into the extent of these other noise sources (mapping the pressure on the ecosystems) and understanding the effects of these noise sources on the organisms (mapping the impact).

4.1 Echosounders and sonars

One of the most ubiquitous sound sources present in our oceans today is represented by commercial shipboard sonar systems (i.e. echosounders; Merchant et al., 2020). Commercial sonar systems are widely used in a variety of marine activities, including science, fishery industry, oceanographic research, benthic habitat mapping, and geophysical exploration (Mayer, 2006; Foote, 2009), in addition to the more traditional navigation and military uses. Many generic 'fish-finders' are also in use on recreational vessels, these represent a lower-cost alternative to scientific echosounders and their potential effects are largely unknown (Cholewiak et al., 2017). Many commercial sonar systems are categorized into one of three main classes: single-beam echosounders (SBES), side-scanning sonars (SSS) or multibeam sonars (MBES). Typical frequency ranges for these systems fall between 12 kHz and 700 kHz, with maximal source levels often ranging from 210 to 240 dB re 1 µPa at 1 m (Lurton and DeRuiter, 2011). A notable exception is military antisubmarine warfare (ASW) sonars, which typically have peak frequencies below 10 kHz. These sonars, however, are already covered by the impulsive noise indicator (MSFD criterion D11C1). While SBES are categorized by narrow apertures (typically 2–12°), with most energy concentrated directly below the ship, MBES may be configured with many beams spanning up to 150° or more. Additionally, omnidirectional sonars have become popular for long-range fish detection (Cholewiak et al., 2017).

Lurton and DeRuiter (2011) tried to estimate the potential effects of echosounders employed in hydrography and seafloor-mapping activities to marine mammals by analysing different cases. Their conclusions suggested that while echosounders may transmit at high sound pressure levels, the very short pulse duration and narrow degree of spatial ensonification (in the case of SBES) make them unlikely to cause physical damage to marine mammal auditory systems. However, the authors did not rule out potential behavioural effects at ranges on the order of kilometres (Lurton and DeRuiter, 2011). Behavioural disturbances caused by echosounders have been confirmed in several case studies. For example, in a recent experiment 5 pilot whales (*Globicephala macrorhynchus*) were equipped with telemetry tags and exposed to a Simrad EK60 commercial echosounder with maximum received levels (RL) that ranged between 117 and 125 dB re 1 µPa. The analysis suggested that during exposure, pilot whales changed their heading more frequently. The authors suggest that this could represent an increased level of vigilance towards the sound source (Quick et al., 2017). Another study that tested the same echosounder model on beaked whales showed that animals were significantly less likely to be detected acoustically when the echosounder was active. These results indicated that beaked whales both detected and changed their acoustic behaviour in response to echosounders noise; the authors inferred that the interruption of foraging behaviour and the avoidance of echosounder noise could be detrimental for the animal fitness (Cholewiak et al., 2017). Off Madagascar, a mass stranding event of melon-headed whales (*Peponocephala electra*), in which an estimated 50 animals died, was probably triggered by the use of a 12 kHz multibeam echosounder that was operated in association with seismic exploration (Southall et al., 2013).

Echosounders also have a clear impact on seals; in 2014, Hastie et al. (2014) tested the effects of two sonar systems (200 and 375 kHz systems) on a grey seal population. Results from captive seals indicated that both systems had significant effects on the individuals' behaviour. Specifically, the use of the 200 kHz sonar pushed seals to spend significantly more time hauled out. While the 375 kHz sonar was active, seals remained in the water but displayed spatial avoidance from the sound source. These results suggested that although peak sonar frequencies were abundantly above seals' hearing ranges, high levels of sound present within their hearing ranges elicited behavioural responses. These findings have been confirmed by Deng et al. (2014) in a study that looked at the spectral properties of the acoustic signals produced by three commercially available echosounders (SM2000 multibeam imaging sonar, DT-X Digital Scientific Echosounder, and Model 965 multibeam imaging sonar). All three models were found to generate sub-harmonic sounds at frequencies that ranged from 90 to 130 kHz, below the carrier frequency advertised by manufacturers and within the hearing range of some marine mammals (e.g. killer whales, false killer whales, beluga whales, Atlantic bottlenose dolphins, harbour porpoises, among others). The authors suggested that although the amplitudes of these sub-harmonic sounds are not likely to cause any physical injury, they could potentially affect the behaviour of marine mammals in proximity to the sources. Excluding echosounders from environmental impact analysis based solely on the carrier frequency output in relation to the range of marine mammal hearing should be reconsidered (Deng et al., 2014).

A potential solution to minimise sound exposure levels (corresponding to the received sound intensity integrated over time) of echosounders could be to employ them in a more adaptive and integrated way together with the other safety tools present onboard the vessels (GPS, radar, AIS). For example, echosounder that are used for navigation could be turned off, or decrease the pinging frequency, when the vessel is located in deep waters or areas that do not present an imminent danger to navigation security, this could be enabled through integration of echosounder and GPS data.

4.2 Acoustic deterrence devices (pingers and seal scarers)

Net pingers and seal scarers are devices used to deter harbour porpoises and seals from fishing gear, aquaculture and construction installations; they are often referred as acoustic deterrent devices or acoustic harassment devices receptively (ADDs or AHDs). Net pingers use many different types of signals, with peak frequencies as low as 10-12 kHz and as high as 70-100 kHz. Source levels also vary, but are generally not higher than 160 dB re 1µPa at 1 m distance (Carlström et al., 2009; Gönener and Bilgin, 2009; Larsen and Eigaard, 2014; Kyhn et al., 2015). Seal scarers, on the other hand, are substantially more powerful, with source levels up to 195 dB re 1 µPa at 1 m with a frequency range from 0.5 to 40 kHz (Lepper et al., 2014; Todd et al., 2021). Length and interval between seal scarers pulses are often randomized to decrease the potential for animals habituating to the sounds, in order to maintain aversion effects over time (Hermannsen et al., 2015a; Gordon et al., 2019).

The use of net pingers around gill nets has been shown to reduce the rate of porpoise by-catch significantly in experimental studies (e.g. Gönener and Bilgin, 2009; Larsen and Eigaard, 2014). However, several studies highlighted also that net pingers can cause habitat displacement. For example, Carlström et al. (2009) investigated how the echolocation rates of harbour porpoises were affected by net pinger activity. Results showed that echolocation rates decreased by 50-100 % at recording location placed at 500 m from the pingers. In a similar experiment, over a longer time frame (28 days), Kyhn et al. (2015) recorded a decrease up to 65% in harbour porpoise detections during the entire period in which net pingers were active over an area of several km. As suggested by Kyhn et al. (2015), future research should be focused on the development of low source level net pingers that could be audible only within close range of the net; this would allow to reduce noise pollution as well as habitat loss.

Seal scarers have higher source levels compared to net pingers and are calibrated to broadcast signals predominantly in the seals hearing range at levels that are directly painful to the animals. Different studies looked at the effects that seal scarers might have on seals and results seem to be contradictory. Mikkelsen et al. (2017) exposed harbour seals and harbour porpoises to 500 ms tone bursts at 12 kHz with a source peak-to-peak level of 165 dB re 1 µPa. Their results indicated that while harbour porpoises showed avoidance up to ranges of 525 m from the source, harbour seals sightings increased during sound exposure within 100 m of the loudspeaker. Similar lack of avoidance by harbour seals was documented also in the Bay of Fundy, where some individuals were seen as close as 45 m to an active seal scarer (Jacobs and Terhune, 2002). Conversely, Gordon et al. (2019) observed that all seal observed within an approximate range of 1000 m responded to the seal scarer playback (predicted received levels: 134.6 dB RMS re 1 µPa). However, the authors highlighted also that the seal responses did not always result in substantial movements away from the source. The maximum response range was 3123 m (predicted RL: 111 dB RMS re 1 µPa). Graham et al. (2009) tested the effectiveness of seal scarers in two Scottish rivers used for salmon rod fisheries. The seal scarers were used to deter seals from a specific area of river and as a barrier to the upstream movement. The results suggested that the used of seal scarers reduced the probability of a seal being sighted upstream of the AHD by roughly 50%. Seal responses to seal scarers have been tested also by Götz and Janik (2010) who observed avoidance behaviour at received levels of 135–144 dB re. 1 µPa. Interestingly, in a concurrent experiment with food presentation, captive individuals habituated quickly to sounds presented at normalised received levels of 146 dB re. 1 µPa (RMS). These findings highlight how behavioural context (in this case motivation to approach the food) could play an important role in responses to acoustic deterrence stimuli, and why it should always be considered, when possible, to measure the impact of anthropogenic noise.

While the results regarding the effects of AHDs in seals are mixed, or at least confounded by variables such as behavioural context, there seem to be a consensus in the literature on the negative impacts of these devices on harbour porpoises. A study that was conducted in the German North Sea, using passive acoustic monitoring and simultaneous aerial surveying showed that

AHDs had a significant deterrence effect on harbour porpoises up to 7.5 km away, with received levels at about 113 dB re. 1 µPa (RMS) (Brandt et al., 2013); within 750 m of the recording devices, harbour porpoise detection decreased by 52-95% of the value before the seal scarer was activated. Furthermore, the aerial survey revealed a significant decrease in porpoise density from 2.4 porpoises km^{-2} to 0.3 porpoises km^{-2} before and during seal scarer operation respectively, over a study area of 990 km^2. Hermannsen et al. (2017) reached similar conclusions in their study, in which they estimated a potential deterrence distance for harbour porpoises of 3.1 km from a seal scarer device. In a review that considered different studies on the effects of seal scarers on harbour porpoise, the authors indicated that minimum deterrence distances for porpoises might vary between 200-350 m (100% individuals deterred) and 1300-1900 m (less than 100% individuals deterred; Hermannsen et al., 2015a). These studies have raised concerns regarding the unwanted disturbance and habitat loss that the use of seal scarers in fish farms and offshore constructions might cause to harbour porpoise populations; therefore, caution should be applied when planning the use of these devices as potential mitigation measures (Brandt et al., 2013).

4.3 Sub-bottom profiling activities

Acoustic Sub-Bottom Profiling (SBP) systems are used to determine physical properties of the sea floor and to image and characterise geological information a few metres below the sea floor. SBP systems operate with various types of sound sources and frequencies (Table 4.1). Different SBP systems are used depending on the objectives of the survey, water depths and prior knowledge of the rock types (if known). For example, the 'pinger' is a high frequency system which operates on a range of single frequencies between 3.5 kHz and 7 kHz. Depending on various factors, such as the type of sediment and the sound source characteristics (frequency, power), SBPs can achieve sea floor penetration from just a few meters to more than 50 m and vertical resolution (layer thickness) down to approximately 0.3 m. The non-linear parametric sub-bottom profilers simultaneously transmit two signals of slightly different high frequencies (e.g. 100 and 110 kHz). Their interaction generates by interference a new low-frequency signal (with the difference frequency). They can achieve very high vertical resolution and are particularly good to use in shallow water environments. Furthermore, they have the advantage of an extremely narrow beamwidth, due to the high primary frequencies), which limits the leakage of acoustic energy to the sides, thereby reducing the horizontal extent of any disturbance caused by the signal.

Table 4.1. Specifications of common SBP systems. Table adapted from Geoscience Australia (2020), SL values from Crocker et al. (2019)

System	Main frq. range (kHz)	SL (dB re 1 µPa·m)	Penetration depth
Parametric	~100		< 100 m, vertical resolution < 0.05 m
'Chirper'	3 - 40	199 - 208	< 100 m, vertical resolution ~0.05 m
'Pinger'	3.5 - 7		10 m to 50 m, vertical resolution 0.2 m
'Boomer'	0.5 - 5	200 -216	30 to 100 m, vertical resolution 0.3 to 1 m
'Sparker'	0.05 - 4	207 - 223	To 1,000 m (ideal), vertical resolution >2 m

5 Concluding remarks

Human-made underwater noise has been recognized as a significant pressure on the marine environment. Because of this recognition, significant progress has been made during the last two decades in the understanding of the impact of noise on marine organisms and means to regulate and mitigate this impact. Substantial work remains, however, as indicated in the HELCOM Regional Action Plan on Underwater noise, the Baltic Sea Action Plan and the HELCOM Science Agenda.

For the two main types of underwater noise sources - low frequency impulsive noise sources and low frequency continuous noise – progress has been made through monitoring programs related to the EU Marine Strategy Framework Directive. Actions for these types of noise are therefore in the first extent related to improving the extent and quality of the monitoring programs to understand the spatio-temporal extent of the noise and quantify the impact. Secondly, and equally important, is to develop new tools for management and regulation of the noisy activities and extend and improve existing regulations, in order to reduce noise emissions and when they cannot be reduced, to reduce the impact of the noise on sensitive organisms. Such reductions in emissions can be achieved by implementing best available technology and best ecological practice (BAT and BEP) whenever possible, and at the same time secure that technologies and operational protocols continue to improve.

A significant number of noise sources are currently unregulated, largely due to lack of empirical evidence about the possible impact on marine organisms. For these noise sources, the primary goal is to combine monitoring to describe the spatio-temporal extent of these sources (mapping the pressure), with experimental studies to quantify the magnitude of potential impact from the noise, whereby the possible need for regulation of these activities can be elucidated.

6 References

Aguilar, N., and V. Martín. 2007. Canary Islands Naval Moratoria. In: T. Agardy, N. Aguilar, A. Cañadas, M. Engel, A. Frantzis, L. Hatch, E. Hoyt, K. Kaschner, E. LaBrecque, V. Martin, G. Notarbartolo di Sciara, G. Pavan, A. Servidio, B. Smith, J. Wang, L. Weilgart, B. Wintle and A. Wright, editors, A Global Scientific Workshop on Spatio-Temporal Management of Noise No. Report of the Scientific Workshop. p. 44.

Ahn, K., G.-H. Choi, D.-I. Son, and K.-P. Rhee. 2012. Hydrodynamic characteristics of X-Twisted rudder for large container carriers. International Journal of Naval Architecture and Ocean Engineering 4(3):322-334. doi: https://doi.org/10.2478/IJNAOE-2013-0100

Aktas, B., N. Yilmaz, M. Atlar, N. Sasaki, P. Fitzsimmons, and D. Taylor. 2020. Suppression of Tip Vortex Cavitation Noise of Propellers using PressurePores™ Technology. J. Mar. Sci. Eng. 8(158)

American National Standards Institute. 2013. American National Standard Acoustical Terminology (ANSI/ASA S1.1-2013). Acoustical Society of America, Melville, NY, USA.

Andersen, P., J. Friesch, J. Kappel, L. Lundegaard, and G. Patience. 2005. Development of a Marine Propeller With Nonplanar Lifting Surfaces. Marine Technology 42:144-158.

Andersen, P., J. Kappel, and E. Spangenberg. 2009. Aspects of Propeller Developments for a Submarine First International Symposium on Marine Propulsors, Trondheim, Norway.

Anderson, P. A., I. K. Berzins, F. Fogarty, H. J. Hamlin, and L. J. Guillette. 2011. Sound, stress, and seahorses: The consequences of a noisy environment to animal health. Aquaculture 311(1):129-138. doi: https://doi.org/10.1016/j.aquaculture.2010.11.013

Anderwald, P., A. Brandecker, M. Coleman, C. Collins, H. Denniston, M. D. Haberlin, O. D. M, R. Pinfield, F. Visser, and L. Walshe. 2013. Displacement responses of a mysticete, an odontocete, and a phocid seal to construction-related vessel traffic. Endangered Species Research 21(3):231-240.

Andrew, R. K., B. M. Howe, J. A. Mercer, and M. A. Dzieciuch. 2002. Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast. Acoustics Research Letters Online 3(2):65-70. doi: 10.1121/1.1461915

AQUO. 2015. Guidelines for regulation on uw noise from commercial shipping.

Atlar, M., E. Glover, M. Candries, R. Mutton, and C. Anderson. 2002. The effect of a foul release coating on propeller performance. In: International conference on Marine Science and Technology for Environmental Sustainability (ENSUS 2002), Newcastle upon Tyne, UK

Bagheri, M. R., M. S. Seif, and H. Mehdigholi. 2017. An Experimental Study on the Effect of IS700 Coating on the Cavitation Inception and Development, and Noise Reduction of a Marine Propeller. Journal of Applied Mechanical Engineering 6(3):267 - 274. doi: doi: 10.4172/2168-9873.1000267

Bailey, H., B. Senior, D. Simmons, J. Rusin, G. Picken, and P. M. Thompson. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. Marine Pollution Bulletin 60(6):888-897. doi: https://doi.org/10.1016/j.marpolbul.2010.01.003

Barlow, J. 1988. Harbor porpoise, *Phocoena phocoena*, abundance estimation for California, Oregon, and Washington: I. Ship surveys. Fishery Bulletin 86:417-432.

Bas, A. A., F. Christiansen, A. Amaha Ozturk, B. Ozturk, and C. McIntosh. 2017. The effects of marine traffic on the behaviour of Black Sea harbour porpoises (*Phocoena phocoena relicta*) within the Istanbul Strait, Turkey. PLoS One 12(3):e0172970. doi: 10.1371/journal.pone.0172970

Bellmann, M., H. Holst, and M. Müller. 2014. Offshore-Windpark „DanTysk" Effizienzkontrolle Hydroschallmessungen. Installationen der Gründungsstrukturen (Monopiles) der 80 Windenergieanlagen und der Umspannstation (Jacket) Darstellung sämtlicher Hydroschallmessungen und Evaluation der eingesetzten Schallminderungssysteme.

Bellmann, M. A. 2014. Overview of existing noise mitigation systems for reducing pile-driving noise, Institute of Noise Control Engineering.

Bellmann, M. A., J. Brinkmann, A. May, T. Wendt, S. Gerlach, and P. Remmers. 2020. Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values. Report to the Federal Maritime and Hydrographic Agency, Oldenburg, Germany.

Bernaldo de Quiros, Y., A. Fernandez, R. W. Baird, R. L. Brownell, Jr., N. Aguilar de Soto, D. Allen, M. Arbelo, M. Arregui, A. Costidis, A. Fahlman, A. Frantzis, F. M. D. Gulland, M. Iniguez, M. Johnson, A. Komnenou, H. Koopman, D. A. Pabst, W. D. Roe, E. Sierra, M. Tejedor, and G. Schorr. 2019. Advances in research on the impacts of anti-submarine sonar on beaked whales. Proceedings. Biological sciences / The Royal Society 286(1895):20182533. doi: 10.1098/rspb.2018.2533

Blackwell, S. B., C. S. Nations, T. L. McDonald, A. M. Thode, D. Mathias, K. H. Kim, C. R. Greene, Jr., and A. M. Macrander. 2015. Effects of airgun sounds on bowhead whale calling rates: evidence for two behavioral thresholds. PLoS One 10(6):e0125720-e0125720. doi: 10.1371/journal.pone.0125720

Blundell, G. M., and G. W. Pendleton. 2015. Factors Affecting Haul-Out Behavior of Harbor Seals (Phoca vitulina) in Tidewater Glacier Inlets in Alaska: Can Tourism Vessels and Seals Coexist? PLoS One 10(5):e0125486-e0125486. doi: 10.1371/journal.pone.0125486

Brandt, M., C. Hoeschle, A. Diederichs, K. Betke, R. Matuschek, S. Witte, and G. Nehls. 2013. Far-reaching effects of a seal scarer on harbour porpoises, Phocoena phocoena. Aquatic Conservation Marine and Freshwater Ecosystems 23:222-232. doi: 10.1002/aqc.2311

Brandt, M. J., A. Diederichs, K. Betke, and G. Nehls. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series 421:205-216.

Bruns, B., C. Kuhn, P. Stein, J. Gatterman, and K.-H. Elmer. 2014. The new noise mitigation system 'Hydro Sound Dampers': history of development with several hydro sound and vibration measurements Inter-noise 2014, Melbourne, Australia.

Bröker, K. C. 2019. An Overview of Potential Impacts of Hydrocarbon Exploration and Production on Marine Mammals and Associated Monitoring and Mitigation Meas. Aquatic Mammals 45(6):576-611. doi: 10.1578/am.45.6.2019.576

Carchen, A., N. Sasaki, B. Aktas, S. Turkmen, and M. Atlar. 2015. DESIGN AND REVIEW OF THE NEW NPT PROPELLER FOR THE PRINCESS ROYAL.

Carlström, J., P. Berggren, and N. J. C. Tregenza. 2009. Spatial and temporal impact of pingers on porpoises. Canadian Journal of Fisheries and Aquatic Sciences 66(1):72-82. doi: 10.1139/F08-186

Casper, B. M., M. E. Smith, M. B. Halvorsen, H. Sun, T. J. Carlson, and A. N. Popper. 2013. Effects of exposure to pile driving sounds on fish inner ear tissues. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology 166(2):352-360. doi: https://doi.org/10.1016/j.cbpa.2013.07.008

Castellote, M., C. W. Clark, and M. O. Lammers. 2012. Acoustic and behavioural changes by fin whales (Balaenoptera physalus) in response to shipping and airgun noise. Biol. Cons. 147(1):115-122. doi: 10.1016/j.biocon.2011.12.021

Cerchio, S., S. Strindberg, T. Collins, C. Bennett, and H. Rosenbaum. 2014. Seismic surveys negatively affect humpback whale singing activity off northern Angola. PLoS One 9(3):e86464-e86464. doi: 10.1371/journal.pone.0086464

Cholewiak, D., A. I. DeAngelis, D. Palka, P. J. Corkeron, and S. M. V. Parijs. 2017. Beaked whales demonstrate a marked acoustic response to the use of shipboard echosounders. Royal Society Open Science 4(12):170940. doi: doi:10.1098/rsos.170940

Claridge, D. E. 2013. Population ecology of Blainville's beaked whales (*Mesoplodon densirostris*), University of St Andrews, St Andrews, Scotland.

Clausen, K. T., M. Wahlberg, K. Beedholm, S. Deruiter, and P. T. Madsen. 2010. Click communication in harbour porpoises (*Phocoena phocoena*). Bioacoustics 20(1):1-28. (Article)

Crocker, S. E., F. D. Fratantonio, P. E. Hart, D. S. Foster, T. F. O'Brien, and S. Labak. 2019. Measurement of Sounds Emitted by Certain High-Resolution

Geophysical Survey Systems. IEEE Journal of Oceanic Engineering 44(3):796-813. doi: 10.1109/JOE.2018.2829958

D'Amico, A., R. C. Gisiner, D. R. Ketten, J. A. Hammock, C. Johnson, P. L. Tyack, and J. Mead. 2009. Beaked Whale Strandings and Naval Exercises. Aquatic Mammals 35(4):452-472. doi: 10.1578/am.35.4.2009.452

Danish Energy Agency. 2022. Guideline for underwater noise. Installation of impact or vibratory driven piles, Danish Ministry of Energy, Copenhagen.

Davidson, J., J. Bebak, and P. Mazik. 2009. The effects of aquaculture production noise on the growth, condition factor, feed conversion, and survival of rainbow trout, Oncorhynchus mykiss. Aquaculture 288(3):337-343. doi: https://doi.org/10.1016/j.aquaculture.2008.11.037

de Soto, N. A., N. Delorme, J. Atkins, S. Howard, J. Williams, and M. Johnson. 2013. Anthropogenic noise causes body malformations and delays development in marine larvae. Scientific Reports 3(1):2831. doi: 10.1038/srep02831

Dekeling, R. P. A., M. L. Tasker, A. J. Van der Graaf, M. A. Ainslie, M. H. Andersson, M. André, J. F. Borsani, K. Brensing, M. Castellote, D. Cronin, J. Dalen, T. Folegot, R. Leaper, J. Pajala, P. Redman, S. P. Robinson, P. Sigray, G. Sutton, F. Thomsen, S. Werner, D. Wittekind, and J. V. Young. 2014. Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications, Luxembourg.

Deng, Z. D., B. L. Southall, T. J. Carlson, J. Xu, J. J. Martinez, M. A. Weiland, and J. M. Ingraham. 2014. 200 kHz Commercial Sonar Systems Generate Lower Frequency Side Lobes Audible to Some Marine Mammals. PLoS One 9(4):e95315. doi: 10.1371/journal.pone.0095315

DeRuiter, S. L., B. L. Southall, J. Calambokidis, W. M. Zimmer, D. Sadykova, E. A. Falcone, A. S. Friedlaender, J. E. Joseph, D. Moretti, G. S. Schorr, L. Thomas, and P. L. Tyack. 2013. First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. Biol Lett 9(4):20130223. doi: 10.1098/rsbl.2013.0223

Di Iorio, L., and C. W. Clark. 2010. Exposure to seismic survey alters blue whale acoustic communication. Biol. Lett. 6(1):51-54. doi: 10.1098/rsbl.2009.0651

Dolman, S., C. Weir, and M. Jasny. 2009. Comparative review of marine mammal guidance implemented during naval exercises. Marine Pollution Bulletin 58:465-477. doi: 10.1016/j.marpolbul.2008.11.013

Dunlop, R. A., M. J. Noad, R. D. McCauley, E. Kniest, R. Slade, D. Paton, and D. H. Cato. 2017. The behavioural response of migrating humpback whales to a full seismic airgun array. Proceedings. Biological sciences 284(1869):20171901. doi: 10.1098/rspb.2017.1901

Dyndo, M., D. M. Wiśniewska, L. Rojano-Doñate, and P. T. Madsen. 2015. Harbour porpoises react to low levels of high frequency vessel noise. Sci. Rep. 5:11083. (Article) doi: 10.1038/srep11083

Dähne, M., A. Gilles, K. Lucke, V. Peschko, S. Adler, K. Krügel, J. Sundermeyer, and U. Siebert. 2013. Effects of pile-driving on harbour porpoises (Phocoena phocoena) at the first offshore wind farm in Germany. Environmental Research Letters 8(2):025002. doi: 10.1088/1748-9326/8/2/025002

Ebrahimi, A., A. H. Razaghian, M. S. Seif, F. Zahedi, and A. Nouri-Borujerdi. 2019. A comprehensive study on noise reduction methods of marine propellers and design procedures. Applied Acoustics 150:55-69. doi: 10.1016/j.apacoust.2018.12.004

ECHO. 2019. 2018 Voluntary vessel slowdown in Haro Strait, Vancouver Fraser Port Authority.

Edrén, S. M. C., S. M. Andersen, J. Teilmann, J. Carstensen, P. B. Harders, R. Dietz, and L. A. Miller. 2010. The effect of a large Danish offshore wind farm on harbor and gray seal haul-out behavior. Mar. Mamm. Sci. 26(3):614-634. doi: 10.1111/j.1748-7692.2009.00364.x

Elmer, K.-H. 2018. Effective Offshore Piling Noise Mitigation in Deep Waters. Journal of Civil Engineering and Architecture 12:662-668. doi: doi: 10.17265/1934-7359/2018.09.006

Erbe, C., S. A. Marley, R. P. Schoeman, J. N. Smith, L. E. Trigg, and C. B. Embling. 2019. The Effects of Ship Noise on Marine Mammals—A Review. Front. Mar. Sci. 6doi: 10.3389/fmars.2019.00606

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke, and R. Dooling. 2016. Communication masking in marine mammals: A review and research strategy. Mar. Poll. Bull. 103(1–2):15-38. doi: 10.1016/j.marpolbul.2015.12.007

European Commission. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). European Commission.

European Commission. 2017. Commission decision (eu) 2017/848 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU.

Fakan, E. P., and M. I. McCormick. 2019. Boat noise affects the early life history of two damselfishes. Marine Pollution Bulletin 141:493-500. doi: https://doi.org/10.1016/j.marpolbul.2019.02.054

Feizi Chekab, M. A., P. Ghadimi, S. R. Djeddi, and M. Soroushan. 2013. Investigation of Different Methods of Noise Reduction for Submerged Marine Propellers and Their Classification. American Journal of Mechanical Engineering 1(2):34-42.

Feizi Chekab, M. A., P. Ghadimi, and H. Nourozi. 2014. Investigation on the effects of increasing the number of blades and using ducts to reducing noise of noncavitating propellers. Journal of Acoustical Society of Iran 1(2)

Fernández, A., J. F. Edwards, F. Rodríguez, A. Espinosa de los Monteros, P. Herráez, P. Castro, J. R. Jaber, V. Martín, and M. Arbelo. 2005. "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (family Ziphiidae) exposed to anthropogenic sonar signals. Vet Pathol 42(4):446-457. doi: 10.1354/vp.42-4-446

Fewtrell, J. L., and R. D. McCauley. 2012. Impact of air gun noise on the behaviour of marine fish and squid. Marine Pollution Bulletin 64(5):984-993. doi: https://doi.org/10.1016/j.marpolbul.2012.02.009

Finneran, J. J. 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. J. Acoust. Soc. Am. 138(3):1702-1726. doi: 10.1121/1.4927418

Foote, K. G. 2009. Acoustic Methods: Brief Review and Prospects for Advancing Fisheries Research. In: R. J. Beamish and B. J. Rothschild, editors, The Future of Fisheries Science in North America, Fish & Fisheries Series No. 31. Springer, Dordrecht.

Frisk, G. 2012. Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. Scientific reports 2:437. doi: 10.1038/srep00437

Gassmann, M., L. Kindberg, W. B.M., H. A. ., S. ., and I. o. O. 2017. 2017. Underwater noise comparison of pre- and post-retrofitted MAERSK G-class container vessels, Scripps Institution of Oceanography, La Jolla, USA.

Gennaro, G., and J. Gonzalez- Adalid. 2012. Improving the Propulsion Efficiency by means of Contracted and Loaded Tip (CLT®) Propellers, Athens, Greece.

Geoscience Australia. 2020. Sub-bottom profilers.

German Federal Ministry for the Environment and Nuclear Safety. 2013. Concept for protection of harbour porpoises from noise impact from offshore wind farms in the German North Sea (Schallschutzkonzept), German Federal Ministry for the Environment and Nuclear Safety, Berlin.

Gillespie, D., J. Gordon, R. Mchugh, D. Mclaren, D. Mellinger, P. Redmond, A. Thode, P. Trinder, and X. Y. Deng. 2008. PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localisation of cetaceans. Proceedings of the Institute of Acoustics 30(5)

Goldbogen, J. A., B. L. Southall, S. L. DeRuiter, J. Calambokidis, A. S. Friedlaender, E. L. Hazen, E. A. Falcone, G. S. Schorr, A. Douglas, D. J. Moretti, C. Kyburg, M. F. McKenna, and P. L. Tyack. 2013. Blue whales respond to simulated mid-frequency military sonar. Proceedings of the Royal Society B: Biological Sciences 280(1765):20130657. doi: doi:10.1098/rspb.2013.0657

Gonzalez- Adalid, J., G. Perez Gomez, M. Perez Sobrino, E. Minguito, A. Garcia, J. Masip, R. Quereda, and P. Beltran. 2006. Full scale comparison of a superferry performance fitted with both High skewed and CLT blades World Maritime Technology Conference, London, UK.

Gordon, J., C. Blight, E. Bryant, and D. Thompson. 2019. Measuring responses of harbour seals to potential aversive acoustic mitigation signals using controlled exposure behavioural response studies. Aquatic Conservation: Marine and Freshwater Ecosystems 29(S1):157-177. doi: 10.1002/aqc.3150

Gordon, J., D. Gillespie, J. Potter, A. Frantzis, M. Simmonds, R. Swift, and D. Thompson. 2003. A Review of The Effects of Seismic Surveys on Marine Mammals. Mar. Technol. Soc. J. 37:16-34. doi: 10.4031/002533203787536998

Graham, I. M., R. N. Harris, B. Denny, D. Fowden, and D. Pullan. 2009. Testing the effectiveness of an acoustic deterrent device for excluding seals from Atlantic salmon rivers in Scotland. ICES Journal of Marine Science 66(5):860-864. doi: 10.1093/icesjms/fsp111

Greene Jr., C. R., and W. J. Richardson. 1988. Characteristics of marine seismic survey sounds in the Beaufort Sea. The Journal of the Acoustical Society of America 83(6):2246-2254. doi: 10.1121/1.396354

Gönener, S., and S. Bilgin. 2009. The effect of pingers on harbour porpoise, Phocoena phocoena bycatch and fishing effort in the turbot gill net fishery in the Turkish Black Sea coast. Turkish Journal of Fisheries and Aquatic Sciences 9:151-157. doi: 10.4194/trjfas.2009.0205

Götz, T., and V. M. Janik. 2010. Aversiveness of sounds in phocid seals: psycho-physiological factors, learning processes and motivation. The Journal of Experimental Biology 213(9):1536-1548. doi: 10.1242/jeb.035535

Halvorsen, M. B., B. M. Casper, F. Matthews, T. J. Carlson, and A. N. Popper. 2012a. Effects of exposure to pile-driving sounds on the lake sturgeon, Nile tilapia and hogchoker. Proceedings of the Royal Society B: Biological Sciences 279(1748):4705-4714. doi: doi:10.1098/rspb.2012.1544

Halvorsen, M. B., B. M. Casper, C. M. Woodley, T. J. Carlson, and A. N. Popper. 2012b. Threshold for Onset of Injury in Chinook Salmon from Exposure to Impulsive Pile Driving Sounds. PLoS One 7(6):e38968. doi: 10.1371/journal.pone.0038968

Halvorsen, M. B., D. G. Zeddies, D. Chicoine, and A. N. Popper. 2013. Effects of low-frequency naval sonar exposure on three species of fish. The Journal of the Acoustical Society of America 134(2):EL205-EL210. doi: 10.1121/1.4812818

Halvorsen, M. B., D. G. Zeddies, W. T. Ellison, D. R. Chicoine, and A. N. Popper. 2012c. Effects of mid-frequency active sonar on hearing in fish. The Journal of the Acoustical Society of America 131(1):599-607. doi: 10.1121/1.3664082

Hansen, H. R., T. Dinham-Peren, and T. Nojiri. 2011. Model and full scale evaluation of a 'propeller boss cap fins' device fitted to an aframax tanker Second International Symposium on Marine Propulsors, Hamburg, Germany.

Harris, R. E., G. W. Miller, and W. J. Richardson. 2001. SEAL RESPONSES TO AIRGUN SOUNDS DURING SUMMER SEISMIC SURVEYS IN THE ALASKAN BEAUFORT SEA. Mar. Mamm. Sci. 17(4):795-812. doi: 10.1111/j.1748-7692.2001.tb01299.x

Harwood, J., and B. Wilson. 2001. The implications of developments on the Atlantic Frontier for marine mammals. Continental Shelf Research 21(8-10):1073-1093. doi: 10.1016/s0278-4343(00)00125-4

Hastie, G. D., C. Donovan, T. Götz, and V. M. Janik. 2014. Behavioral responses by grey seals (*Halichoerus grypus*) to high frequency sonar. Marine Pollution Bulletin 79(1):205-210. doi: https://doi.org/10.1016/j.marpolbul.2013.12.013

Hawkins, A. D., and K. J. Rasmussen. 1978. The calls of gadoid fish. Journal of the Marine Biological Association of the United Kingdom 58(4):891-911. doi: 10.1017/S0025315400056848

Hawkins, A. D., L. Roberts, and S. Cheesman. 2014. Responses of free-living coastal pelagic fish to impulsive sounds. The Journal of the Acoustical Society of America 135(5):3101-3116. doi: 10.1121/1.4870697

HELCOM. 2019. Noise sensitivity of animals in the Baltic Sea.

HELCOM. 2021a. Baltic Sea Action Plan – 2021 update, Helsinki.

HELCOM. 2021b. HELCOM Recommendation 42-43/1. Regional action plan on underwater noise (RAP noise), Helsinki.

Hemmera Envirochem, I. 2016. Vessel Quieting Design, Technology, and Maintenance Options for Potential Inclusion in EcoAction Program Enhancing Cetacean Habitat and Observation Program, Burnaby, Canada.

Herbert-Read, J. E., L. Kremer, R. Bruintjes, A. N. Radford, and C. C. Ioannou. 2017. Anthropogenic noise pollution from pile-driving disrupts the structure and dynamics of fish shoals. Proceedings of the Royal Society B: Biological Sciences 284(1863):20171627. doi: doi:10.1098/rspb.2017.1627

Hermannsen, L., K. Beedholm, J. Tougaard, and P. T. Madsen. 2014. High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (Phocoena phocoena). The Journal of the Acoustical Society of America 136(4):1640-1653. doi: 10.1121/1.4893908

Hermannsen, L., L. Mikkelsen, and J. Tougaard. 2015a. Review: Effects of seal scarers on harbour porpoises, Aarhus University, DCE - Danish Centre for Environment and Energy.

Hermannsen, L., L. Mikkelsen, and J. Tougaard. 2017. The effect of simulated seal scarer sounds on harbour porpoises, Aarhus University, DCE - Danish Centre for Environment and Energy.

Hermannsen, L., J. Tougaard, K. Beedholm, J. Nabe-Nielsen, and P. P. T. Madsen. 2015b. Characteristics and propagation of airgun pulses in shallow water with implications for effects on small marine mammals

Hilliard, L., D. McHorney, M. Palmieri, and G. Pelella. 2014. Catalog of Solutions to Reduce Marine Acoustic Pollution, United States Coast Guard.

Hirst, A., and P. Rodhouse. 2000. Impacts of geophysical seismic surveying on fishing success. Reviews in Fish Biology and Fisheries 10:113-118. doi: 10.1023/A:1008987014736

Houser, D. S., S. W. Martin, and J. J. Finneran. 2013a. Behavioral responses of California sea lions to mid-frequency (3250–3450 Hz) sonar signals. Marine Environmental Research 92:268-278. doi: https://doi.org/10.1016/j.marenvres.2013.10.007

Houser, D. S., S. W. Martin, and J. J. Finneran. 2013b. Exposure amplitude and repetition affect bottlenose dolphin behavioral responses to simulated mid-frequency sonar signals. J. Exp. Mar. Biol. Ecol. 443:123-133. doi: https://doi.org/10.1016/j.jembe.2013.02.043

IMO. 2014. Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life, International Maritime Organisation, London, UK.

Jacobs, S., and J. Terhune. 2002. The effectiveness of acoustic harassment devices in the Bay of Fundy, Canada: Seal reactions and a noise exposure model. Aquat. Mamm. 28

Jepson, P. D., M. Arbelo, R. Deaville, I. A. P. Patterson, P. Castro, J. R. Baker, E. Degollada, H. M. Ross, P. Herraez, A. M. Pocknell, F. Rodriguez, F. E. Howie, A. Espinosa, R. J. Reid, J. R. Jaber, V. Martin, A. A. Cunningham, and A. Fernandez. 2003. Gas-bubble lesions in stranded cetaceans - Was sonar responsible for a spate of whale deaths after an Atlantic military exercise? Nature 425(6958):575-576. doi: 10.1038/425575a

JNCC. 2017. JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys, Joint Nature Conservation Committee.

Jones, I. T., J. A. Stanley, and T. A. Mooney. 2020. Impulsive pile driving noise elicits alarm responses in squid (Doryteuthis pealeii). Marine Pollution Bulletin 150:110792. doi: https://doi.org/10.1016/j.marpolbul.2019.110792

Kane, A. S., J. Song, M. B. Halvorsen, D. L. Miller, J. D. Salierno, L. E. Wysocki, D. Zeddies, and A. N. Popper. 2010. Exposure of fish to high-intensity sonar does not induce acute pathology. Journal of Fish Biology 76(7):1825-1840. doi: 10.1111/j.1095-8649.2010.02626.x

Kaplan, M. B., and S. Solomon. 2016. A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. Marine Policy 73:119-121. doi: 10.1016/j.marpol.2016.07.024

Kastelein, R., L. Huijser, S. Cornelisse, L. Helder-Hoek, N. Jennings, and C. Jong. 2019. Effect of Pile-Driving Playback Sound Level on Fish-Catching Efficiency in Harbor Porpoises (Phocoena phocoena). Aquatic Mammals 45:398-410. doi: 10.1578/AM.45.4.2019.398

Kastelein, R. A., C. A. F. de Jong, J. Tougaard, L. Helder-Hoek, and L. N. Defillet. 2022. Behavioral Responses of a Harbor Porpoise (Phocoena phocoena) Depend on the Frequency Content of Pile-Driving Sounds. Aquat. Mamm. 48(2):97-109. doi: 10.1578/am.48.2.2022.97

Kastelein, R. A., R. Gransier, J. Schop, and L. Hoek. 2015a. Effects of exposure to intermittent and continuous 6–7 kHz sonar sweeps on harbor porpoise (Phocoena phocoena) hearing. The Journal of the Acoustical Society of America 137(4):1623-1633. doi: 10.1121/1.4916590

Kastelein, R. A., L. Helder-Hoek, G. Janssens, R. Gransier, and T. Johansson. 2015b. Behavioral Responses of Harbor Seals (*Phoca vitulina*) to Sonar Signals in the 25-kHz Range. Aquat. Mamm. 41(4):388-399.

Kastelein, R. A., L. Hoek, R. Gransier, M. Rambags, and N. Claeys. 2014. Effect of level, duration, and inter-pulse interval of 1–2 kHz sonar signal exposures on harbor porpoise hearing. The Journal of the Acoustical Society of America 136(1):412-422. doi: 10.1121/1.4883596

Kastelein, R. A., D. van Heerden, R. Gransier, and L. Hoek. 2013. Behavioral responses of a harbor porpoise (Phocoena phocoena) to playbacks of broadband pile driving sounds. Marine Environmental Research 92:206-214. doi: https://doi.org/10.1016/j.marenvres.2013.09.020

Kavanagh, A. S., M. Nykänen, W. Hunt, N. Richardson, and M. J. Jessopp. 2019. Seismic surveys reduce cetacean sightings across a large marine ecosystem. Scientific Reports 9(1):19164. doi: 10.1038/s41598-019-55500-4

Ketten, D. R., J. Lien, and S. Todd. 1993. Blast injury in humpback whale ears: Evidence and implications. The Journal of the Acoustical Society of America 94(3):1849-1850. doi: 10.1121/1.407688

Koschinski, S., and K. Lüdemann. 2020. Noise mitigation for the construction of increasingly large offshore wind turbines. Technical options for complying with noise limits, Report commissioned by the Federal Agency for Nature Conservation, Isle of Vilm, Germany.

Kuhn, C., B. Bruns, J. Fischer, J. Gattermann, and K.-H. Elmer. 2012. Development of a New Underwater Piling Noise Mitigation System: Using Hydro Sound Dampers (HSD). In: ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering. p 195-202.

Kvadsheim, P. H., E. M. Sevaldsen, L. P. Folkow, and A. S. Blix. 2010. Behavioural and physiological responses of hooded seals (*Cystophora cristata*) to 1 to 7 khz sonar signals. Aquat. Mamm. 36(3):239-247. doi: 10.1578/am.36.3.2010.239

Kyhn, L. A., D. Boertman, J. Tougaard, K. Johansen, and A. Mosbech. 2011a. Guidelines to environmental impact assessment of seismic activities in Greenland waters. 3rd revised edition, Roskilde, Denmark.

Kyhn, L. A., D. Boertmann, J. Tougaard, K. Johansen, and A. Mosbech. 2011b. Guidelines to environmental impact assessment of seismic activities in Greenland waters, Danish Center for Environment and Energy

Kyhn, L. A., P. B. Jørgensen, J. Carstensen, N. I. Bech, J. Tougaard, T. Dabelsteen, and J. Teilmann. 2015. Pingers cause temporary habitat displacement in the harbour porpoise Phocoena phocoena. Marine Ecology Progress Series 526:253-265.

Kyhn, L. A., D. M. Wisniewska, K. Beedholm, J. Tougaard, M. Simon, A. Mosbech, and P. T. Madsen. 2019. Basin-wide contributions to the underwater soundscape by multiple seismic surveys with implications for marine mammals in Baffin Bay, Greenland. Mar. Poll. Bull. 138:474-490. doi: https://doi.org/10.1016/j.marpolbul.2018.11.038

Lance, R. M., and C. R. Bass. 2015. Underwater blast injury: a review of standards. Diving Hyperb. Med. 45(3):190-199.

Lance, R. M., B. Capehart, O. Kadro, and C. R. Bass. 2015. Human injury criteria for underwater blasts. PLoS One 10(11):e0143485. doi: 10.1371/journal.pone.0143485

Larsen, F., and O. R. Eigaard. 2014. Acoustic alarms reduce bycatch of harbour porpoises in Danish North Sea gillnet fisheries. Fisheries Research 153:108-112. doi: https://doi.org/10.1016/j.fishres.2014.01.010

Leaper, R., M. Renilson, and R. Conor. 2014. Reducing underwater noise from large commercial ships: current status and future directions. The Journal of Ocean Technology 9(1)

Lepper, P. A., J. Gordon, C. Booth, P. Theobald, S. P. Robinson, S. Northridge, and L. Wang. 2014. Establishing the sensitivity of cetaceans and seals to acoustic deterrent devices in Scotland. Scottish Natural Heritage Commissioned Report No. 517.

Ligtelijn, J. T. 2007. Advantages of different propellers for minimising noise generation. In: 3rd International Ship Noise and Vibration Conference, London, UK

Lombard, E. 1911. Le signe de l'élévation de la voix. Annales des Maladies de l'Oreille, du Larynx du Nez et du Pharynx 37:101–119.

Lurton, X., and S. DeRuiter. 2011. Sound Radiation of Seafloor-Mapping Echosounders in the Water Column, In Relation to the Risks Posed to Marine Mammals. The International Hydrographic Review (6)

Lyamin, O., S. Korneva, V. Rozhnov, and L. Mukhametov. 2015. Cardiorespiratory Responses to Acoustic Noise in Belugas. Advances in experimental medicine and biology 875:665-672. doi: 10.1007/978-1-4939-2981-8_80

Ma, C., H.-p. Cai, Z.-f. Qian, and K. Chen. 2014. The design of propeller and propeller boss cap fins (PBCF) by an integrative method. Journal of Hydrodynamics, Ser. B 26(4):586-593. doi: https://doi.org/10.1016/S1001-6058(14)60066-4

Mappress. 2014. Becker Marine Brings 'Cross Over Rudder' Innovation World Maritime News, https://worldmaritimenews.com/archives/107636/becker-marine-brings-cross-over-rudder-innovation/.

Matczak, M. 2018. QUO VADIS. Exploring the future of shipping in the Baltic Sea, Baltic Lines. Coherent Linear Infrastructures in Baltic Marine Spatial Plans.

Mayer, L. A. 2006. Frontiers in Seafloor Mapping and Visualization. Marine Geophysical Researches 27(1):7-17. doi: 10.1007/s11001-005-0267-x

McDonald, M. A., J. A. Hildebrand, and S. M. Wiggins. 2006. Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. The Journal of the Acoustical Society of America 120(2):711-718. doi: 10.1121/1.2216565

McKenzie Maxon, C. 2012. Offshore pile driving - cofferdam underwater noise measurements, Copenhagen.

Meccanica, S. d. l. N. e. 2014. Unconventional Tip Shape Propellers: 2014 Technology Review, Genoa, Italy.

Merchant, N. D., M. H. Andersson, T. Box, F. Le Courtois, D. Cronin, N. Holdsworth, N. Kinneging, S. Mendes, T. Merck, J. Mouat, A. M. J. Norro, B. Ollivier, C. Pinto, P. Stamp, and J. Tougaard. 2020. Impulsive noise pollution in the Northeast Atlantic: Reported activity during 2015–2017. Mar. Poll. Bull. 152:110951. doi: 10.1016/j.marpolbul.2020.110951

Mewis, F., and U. Hollenbach. 2006. Special measures for improving propulsive efficiency.

Mikkelsen, L., L. Hermannsen, K. Beedholm, P. T. Madsen, and J. Tougaard. 2017. Simulated seal scarer sounds scare porpoises, but not seals: species-specific responses to 12 kHz deterrence sounds. Royal Society open science 4(7):170286-170286. doi: 10.1098/rsos.170286

Moore, J. E., and J. P. Barlow. 2013. Declining Abundance of Beaked Whales (Family Ziphiidae) in the California Current Large Marine Ecosystem. PLoS One 8(1):e52770. doi: 10.1371/journal.pone.0052770

Morgan, M. J., C. E. Wilson, and L. W. Crim. 1999. The effect of stress on reproduction in Atlantic cod. Journal of Fish Biology 54(3):477-488. doi: 10.1111/j.1095-8649.1999.tb00629.x

Nedelec, S. L., S. D. Simpson, E. L. Morley, B. Nedelec, and A. N. Radford. 2015. Impacts of regular and random noise on the behaviour, growth and development of larval Atlantic cod (<i>Gadus morhua</i>). Proceedings of the Royal Society B: Biological Sciences 282(1817):20151943. doi: doi:10.1098/rspb.2015.1943

Nedwell, J., J. Langworthy, and D. Howell. 2003. Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise, COWRIE.

Nieukirk, S. L., D. K. Mellinger, S. E. Moore, K. Klinck, R. P. Dziak, and J. Goslin. 2012. Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2009. The Journal of the Acoustical Society of America 131(2):1102-1112. doi: 10.1121/1.3672648

NMFS. 2018. 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0):

Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. NOAA Technical Memorandum NMFS-OPR-59, NOAA.

Nordlund, N., and P. Kvadsheim. 2015. SONATE 2015 – a decision aid tool to mitigate the impact of sonar operations on marine life, Norwegian Defence Research Establishment (FFI).

Ouchi, K., and M. Tamashima. 1992. A study on correlation between propeller pitch distribution and improvement of propeller efficiency by PBCF. Journal of the Kansai Society of Naval Architects 217:51-60.

Ouchi, K., M. Tamashima, and K. Arai. 1991. Reduction of propeller cavitation noise by PBCF (propeller boss cap fins). Journal of the Kansai Society of Naval Architects 216:65 - 73.

Palka, D. L., and P. S. Hammond. 2001. Accounting for responsive movement in line transect estimates of abundance. Canadian Journal of Fisheries and Aquatic Sciences 58(4):777-787. doi: 10.1139/f01-024

Parsons, E. C. M. 2017. Impacts of Navy Sonar on Whales and Dolphins: Now beyond a Smoking Gun? Frontiers in Marine Science 4(295)(Review) doi: 10.3389/fmars.2017.00295

Parsons, E. C. M., S. J. Dolman, A. J. Wright, N. A. Rose, and W. C. G. Burns. 2008. Navy sonar and cetaceans: Just how much does the gun need to smoke before we act? Marine Pollution Bulletin 56(7):1248-1257. doi: https://doi.org/10.1016/j.marpolbul.2008.04.025

Paxton, A. B., J. C. Taylor, D. P. Nowacek, J. Dale, E. Cole, C. M. Voss, and C. H. Peterson. 2017. Seismic survey noise disrupted fish use of a temperate reef. Marine Policy 78:68-73. doi: 10.1016/j.marpol.2016.12.017

Payne, R., and D. Webb. 1971. Orientation by means of long range acoustic signalling in baleen whales. Ann. N. Y. Acad. Sci. 118(1):110-141. doi: 10.1111/j.1749-6632.1971.tb13093.x

Quick, N., L. Scott-Hayward, D. Sadykova, D. Nowacek, and A. Read. 2017. Effects of a scientific echo sounder on the behavior of short-finned pilot whales (*Globicephala macrorhynchus*). Canadian Journal of Fisheries and Aquatic Sciences 74(5):716-726. doi: 10.1139/cjfas-2016-0293

Renilson Marine Consulting Pty, L. 2009. Reducing Underwater Noise Pollution from Large Commercial Vessels

Robinson, S. P., L. Wang, S. H. Cheong, P. A. Lepper, F. Marubini, and J. P. Hartley. 2020. Underwater acoustic characterisation of unexploded ordnance disposal using deflagration. Mar Pollut Bull 160:111646. doi: 10.1016/j.marpolbul.2020.111646

Rolland, R. M., S. E. Parks, K. E. Hunt, M. Castellote, P. J. Corkeron, D. P. Nowacek, S. K. Wasser, and S. D. Kraus. 2012. Evidence that ship noise increases stress in right whales. Proceedings of the Royal Society B: Biological Sciences doi: 10.1098/rspb.2011.2429

Russell, D. J. F., G. D. Hastie, D. Thompson, V. M. Janik, P. S. Hammond, L. A. S. Scott-Hayward, J. Matthiopoulos, E. L. Jones, and B. J. McConnell. 2016. Avoidance of wind farms by harbour seals is limited to pile driving activities. J. Appl. Ecol. 53(6):1642-1652. doi: 10.1111/1365-2664.12678

Sand, O., and P. S. Enger. 1973. Evidence for an auditory function of the swimbladder in the cod. J Exp Biol 59:405-414.

Sand, O., and H. E. Karlsen. 2000. Detection of infrasound and linear acceleration in fishes. Philos. Trans. R. Soc. Lond. B Biol. Sci. 355(1401):1295-1298. doi: 10.1098/rstb.2000.0687

Sarnocińska, J., J. Teilmann, J. D. Balle, F. M. van Beest, M. Delefosse, and J. Tougaard. 2020. Harbor Porpoise (Phocoena phocoena) Reaction to a 3D Seismic Airgun Survey in the North Sea. Frontiers in Marine Science 6(824)(Original Research) doi: 10.3389/fmars.2019.00824

Sasaki, N., and G. Patience. 2005. Evolution of high efficiency propeller with new blade section Motorship Conference, Bilbao, Spain.

Schmidtke, E. 2011. The damping of shockwaves with an air-bubble barrier for the protection of sea mammals.

Schmidtke, E., B. Nützel, and S. Ludwig. 2009. Risk mitigation for sea mammals — The use of air bubbles against shock waves, Rotterdam

Sexton, T. 2007. Underwater Sound Levels Associated with Pile Driving during the Anacortes Ferry Terminal Dolphin Replacement Project, Washington State Department of Transportation, Office of Air Quality and Noise.

Siebert, U., J. Sturznickel, T. Schaffeld, R. Oheim, T. Rolvien, E. Prenger-Berninghoff, P. Wohlsein, J. Lakemeyer, S. Rohner, L. Aroha Schick, S. Gross, D. Nachtsheim, C. Ewers, P. Becher, M. Amling, and M. Morell. 2022. Blast injury on harbour porpoises (Phocoena phocoena) from the Baltic Sea after explosions of deposits of World War II ammunition. Environ Int 159:107014. doi: 10.1016/j.envint.2021.107014

Sierra-Flores, R., T. Atack, H. Migaud, and A. Davie. 2015. Stress response to anthropogenic noise in Atlantic cod Gadus morhua L. Aquacultural Engineering 67:67-76. doi: https://doi.org/10.1016/j.aquaeng.2015.06.003

Sivle, L. D., P. H. Kvadsheim, M. A. Ainslie, A. Solow, N. O. Handegard, N. Nordlund, and F.-P. A. Lam. 2012. Impact of naval sonar signals on Atlantic herring (Clupea harengus) during summer feeding. ICES Journal of Marine Science 69(6):1078-1085. doi: 10.1093/icesjms/fss080

Sivle, L. D., P. H. Kvadsheim, C. Curé, S. Isojunno, P. J. Wensveen, F.-P. A. Lam, F. Visser, L. Kleivane, P. L. Tyack, C. M. Harris, and P. J. O. Miller. 2015. Severity of Expert-Identified Behavioural Responses of Humpback Whale, Mike Whale, and Northern Bottlenose Whale to Naval Sonar. Aquatic Mammals 41(4):469-502. doi: 10.1578/am.41.4.2015.469

Slabbekoorn, H., J. Dalen, D. de Haan, H. V. Winter, C. Radford, M. A. Ainslie, K. D. Heaney, T. van Kooten, L. Thomas, and J. Harwood. 2019. Population-level consequences of seismic surveys on fishes: An interdisciplinary challenge. Fish and Fisheries 20(4):653-685. doi: 10.1111/faf.12367

Smith, D. R., and J. E. Slater. 1988. The Geometry of Marine Propellers, Defence Research Establishment Atlantic, Dartmouth.

Smith, M. E., A. S. Kane, and A. N. Popper. 2004. Noise-induced stress response and hearing loss in goldfish (Carassius auratus). Journal of Experimental Biology 207(3):427-435. doi: 10.1242/jeb.00755

Southall, B. L., A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. Greene, D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack. 2007. Marine Mammal Noise Exposure Criteria. Aquat. Mamm. 33(4):411-414. doi: 10.1578/am.33.4.2007.411

Southall, B. L., J. J. Finneran, C. Reichmuth, P. E. Nachtigall, D. R. Ketten, A. E. Bowles, W. T. Ellison, D. P. Nowacek, and P. L. Tyack. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquat. Mamm. 45(2):125-232. doi: 10.1578/am.45.2.2019.125

Southall, B. L., D. P. Nowacek, A. E. Bowles, V. Senigaglia, L. Bejder, and P. L. Tyack. 2021. Marine Mammal Noise Exposure Criteria: Assessing the Severity of Marine Mammal Behavioral Responses to Human Noise. Aquat. Mamm. 47(5):421-464. doi: 10.1578/am.47.5.2021.421

Southall, B. L., T. Rowles, F. Gulland, R. W. Baird, and P. D. Jepson. 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, International Whaling Commission.

Spence, J. H. 2007. A Summary of Existing and Future Potential Treatments for Reducing Underwater Sounds from Oil and Gas Industry Activities. In: OCEANS 2007. p 1-15.

Spence, J. H., and R. W. Fischer. 2017. Requirements for Reducing Underwater Noise From Ships. IEEE Journal of Oceanic Engineering 42(2):388-398. doi: 10.1109/JOE.2016.2578198

Spiga, I., N. Aldred, and G. S. Caldwell. 2017. Anthropogenic noise compromises the anti-predator behaviour of the European seabass, Dicentrarchus labrax (L.). Marine Pollution Bulletin 122(1):297-305. doi: https://doi.org/10.1016/j.marpolbul.2017.06.067

Sun, Y., Y. Su, X. Wang, and H. Hu. 2016. Experimental and numerical analyses of the hydrodynamic performance of propeller boss cap fins in a propeller-rudder system. Engineering Applications of Computational Fluid Mechanics 10(1):145-159. doi: 10.1080/19942060.2015.1121838

Sundermeyer, J. K., K. Lucke, M. Dähne, A. Gallus, K. Krügel, and U. Siebert. 2012. Effects of Underwater Explosions on Presence and Habitat Use of Harbor Porpoises in the German Baltic Sea In: A. N. P. a. A. Hawkins, editor, The Effects of Noise on Aquatic Life. Advances in experimental medicine and biology, Springer, New York, NY.

Terhune, J. M., R. E. A. Stewart, and K. Ronald. 1979. Influence of vessel noises on underwater vocal activity of harp seals. Canadian Journal of Zoology 57(6):1337-1338. doi: 10.1139/z79-170

Thompson, D., M. Sjoberg, M. E. Bryant, P. Lovell, and A. Bjorge. 1998. Behavioral and physiological responses of harbour (*Phoca vitulina*) and grey (*Halichoerus grypus*) seals to seismic surveys. MAS2C7940098, Report to European Commission of BROMMAD Project.

Thompson, P. M., K. L. Brookes, I. M. Graham, T. R. Barton, K. Needham, G. Bradbury, and N. D. Merchant. 2013. Short-term disturbance by a commercial two-dimensional seismic survey does not lead to long-term displacement of harbour porpoises. Proceedings of the Royal Society B: Biological Sciences 280(1771):20132001. doi: doi:10.1098/rspb.2013.2001

Todd, V. L. G., L. D. Williamson, J. Jiang, S. E. Cox, I. B. Todd, and M. Ruffert. 2021. Prediction of marine mammal auditory-impact risk from Acoustic Deterrent Devices used in Scottish aquaculture. Mar Pollut Bull 165:112171. doi: 10.1016/j.marpolbul.2021.112171

Tougaard, J., K. Beedholm, and P. T. Madsen. 2022. Thresholds for noise induced hearing loss in harbor porpoises and phocid seals. J. Acoust. Soc. Am. 151(6):4252-4263. doi: 10.1121/10.0011560

Tougaard, J., J. Carstensen, J. Teilmann, H. Skov, and P. Rasmussen. 2009. Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (Phocoena phocoena (L.)). The Journal of the Acoustical Society of America 126(1):11-14. doi: 10.1121/1.3132523

Tougaard, J., L. A. Kyhn, M. Amundin, D. Wennerberg, and C. Bordin. 2012. Behavioral Reactions of Harbor Porpoise to Pile-Driving Noise. In: The Effects of Noise on Aquatic Life, New York, NY. p 277-280.

Tripovich, J. S., S. Hall-Aspland, I. Charrier, and J. P. Y. Arnould. 2012. The behavioural response of Australian fur seals to motor boat noise. PLoS One 7(5):e37228-e37228. doi: 10.1371/journal.pone.0037228

Tsouvalas, A., and A. V. Metrikine. 2016. Noise reduction by the application of an air-bubble curtain in offshore pile driving. Journal of Sound and Vibration 371:150-170. doi: 10.1016/j.jsv.2016.02.025

Tyack, P. L. 2008. Implications for marine mammals of large-scale changes in the marine acoustic environment. J. Mammal. 89(3):549-558, 510.

Tyack, P. L., and L. Thomas. 2019. Using dose–response functions to improve calculations of the impact of anthropogenic noise. Aquatic Conservation: Marine and Freshwater Ecosystems 29(S1):242-253. doi: 10.1002/aqc.3149

Tyack, P. L., W. M. X. Zimmer, D. Moretti, B. L. Southall, D. E. Claridge, J. W. Durban, C. W. Clark, A. D'Amico, N. DiMarzio, S. Jarvis, E. McCarthy, R. Morrissey, J. Ward, and I. L. Boyd. 2011. Beaked Whales Respond to Simulated and Actual Navy Sonar. PLoS One 6(3)(Article) doi: e17009

10.1371/journal.pone.0017009

van Beest, F. M., J. Teilmann, L. Hermannsen, A. Galatius, L. Mikkelsen, S. Sveegaard, J. D. Balle, R. Dietz, and J. Nabe-Nielsen. 2018. Fine-scale movement responses of free-ranging harbour porpoises to capture, tagging and short-term noise pulses from a single airgun. Royal Society Open Science 5(1):170110. doi: doi:10.1098/rsos.170110

Van Parijs, S. M. 2003. Aquatic mating in pinnipeds: a review. Aquatic Mammals 29(2):214-226.

Van Parijs, S. M., P. J. Corkeron, J. Harvey, S. A. Hayes, D. K. Mellinger, P. A. Rouget, P. M. Thompson, M. Wahlberg, and K. M. Kovacs. 2003. Patterns in the vocalizations of male harbor seals. The Journal of the Acoustical Society of America 113(6):3403-3410. doi: 10.1121/1.1568943

Verfuss, U. K., D. Gillespie, J. Gordon, T. A. Marques, B. Miller, R. Plunkett, J. A. Theriault, D. J. Tollit, D. P. Zitterbart, P. Hubert, and L. Thomas. 2018. Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. Mar Pollut Bull 126:1-18. doi: 10.1016/j.marpolbul.2017.10.034

Von Benda-Beckmann, A. M., P. J. Wensveen, P. H. Kvadsheim, F. P. Lam, P. J. Miller, P. L. Tyack, and M. A. Ainslie. 2014. Modeling effectiveness of gradual increases in source level to mitigate effects of sonar on marine mammals. Conservation biology : the journal of the Society for Conservation Biology 28(1):119-128. doi: 10.1111/cobi.12162

von Benda-Beckmann, A. M., G. Aarts, H. O. Sertlek, K. Lucke, W. C. Verboom, R. A. Kastelein, D. R. Ketten, R. van Bemmelen, F. P. A. Lam, R. J. Kirkwood, and M. A. Ainslie. 2015. Assessing the Impact of Underwater Clearance of Unexploded Ordnance on Harbour Porpoises (*Phocoena phocoena*) in the Southern North Sea. Aquat. Mamm. 41(4):503-523. (Article) doi: 10.1578/am.41.4.2015.503

Weir, C. R., and S. J. Dolman. 2007. Comparative Review of the Regional Marine Mammal Mitigation Guidelines Implemented During Industrial Seismic Surveys, and Guidance Towards a Worldwide Standard. Journal of International Wildlife Law & Policy 10(1):1-27. doi: 10.1080/13880290701229838

Wensveen, P. J., P. H. Kvadsheim, F. A. Lam, A. M. von Benda-Beckmann, L. D. Sivle, F. Visser, C. Cure, P. L. Tyack, and P. J. O. Miller. 2017. Lack of behavioural responses of humpback whales (Megaptera novaeangliae) indicate limited effectiveness of sonar mitigation. J Exp Biol 220(Pt 22):4150-4161. doi: 10.1242/jeb.161232

Wilson, B., R. S. Batty, and L. M. Dill. 2004. Pacific and Atlantic herring produce burst pulse sounds. Proceedings of the Royal Society of London. Series B: Biological Sciences 271(suppl_3):S95-S97. doi: doi:10.1098/rsbl.2003.0107

WindEurope. 2019. Offshore wind in Europe: Key trends and statistics 2018, Brussels, Belgium.

Wisniewska, D. M., M. Johnson, J. Teilmann, L. Rojano-Donate, J. Shearer, S. Sveegaard, L. A. Miller, U. Siebert, and P. T. Madsen. 2016. Ultra-High

Foraging Rates of Harbor Porpoises Make Them Vulnerable to Anthropogenic Disturbance. Current biology : CB 26(11):1441-1446. doi: 10.1016/j.cub.2016.03.069

Wisniewska, D. M., M. Johnson, J. Teilmann, U. Siebert, A. Galatius, R. Dietz, and P. T. Madsen. 2018. High rates of vessel noise disrupt foraging in wild harbour porpoises (<i>Phocoena phocoena</i>). Proceedings of the Royal Society B: Biological Sciences 285(1872):20172314. doi: doi:10.1098/rspb.2017.2314

Wright, A. J., M. Maar, C. Mohn, J. Nabe-Nielsen, U. Siebert, L. F. Jensen, H. J. Baagøe, and J. Teilmann. 2013. Possible Causes of a Harbour Porpoise Mass Stranding in Danish Waters in 2005. PLoS One 8(2):e55553. doi: 10.1371/journal.pone.0055553

Wright, A. J., N. A. Soto, A. Baldwin, M. Bateson, C. Beale, C. Clark, T. Deak, E. Edwards, A. Fernandez, A. Godinho, L. Hatch, A. Kakuschke, D. Lusseau, D. Martineau, L. Romero, L. Weilgart, B. Wintle, G. N. D. Sciara, and V. Martin. 2007. Anthropogenic noise as a stressor in animals: A multidisciplinary perspective. Int.J.Comp.Psychol. 20(2-3):250-273.

Würsig, B., C. R. Greene, and T. A. Jefferson. 2000. Development of an air bubble curtain to reduce underwater noise of percussive piling. Marine Environmental Research 49(1):79-93. doi: https://doi.org/10.1016/S0141-1136(99)00050-1

Würsig, G. M., and S. D. Adams. 2015. Power without pistons: GTT, CMA CGM and DNV GL present LNGfuelled, turbine-powered mega box ship study. In: D. G. P. Release (ed.), https://www.dnvgl.com/news/power-without-pistons-gtt-cma-cgm-and-dnv-gl-present-lng-fuelledturbine-powered-mega-box-ship-study-45289.

Wysocki, L. E., J. P. Dittami, and F. Ladich. 2006. Ship noise and cortisol secretion in European freshwater fishes. Biol. Conserv. 128(4):501-508. doi: https://doi.org/10.1016/j.biocon.2005.10.020

Yelverton, J. T., D. R. Richmond, E. R. Fletcher, and R. K. Jones. 1973. Safe distances from underwater explosions for mammals and birds. AD-766 952, Albuquerque, New Mexico.

Aarts, G., S. Brasseur, and R. Kirkwood. 2017. Response of grey seals to pile-driving. Wageningen Marine Research report C006/18., Wageningen.

MEASURES FOR REDUCTION OF ANTHROPOGENIC NOISE IN THE BALTIC

Report to the HELCOM SOM project

The recent update of the HELCOM Baltic Sea Action Plan in has created an urgent need for reviewing the major sources of underwater noise, their known and likely impact on the marine environment and possible ways to mitigate the impact. Impulsive noise sources (pile driving, seismic surveys, underwater explosions, low-frequency sonars etc.) are known to cause negative effects in marine mammals and fish. Mitigation includes: a) reduction in produced noise (source modification), b) reduction in radiated noise (abatement) and c) reduction in received noise (restriction of activities in sensitive areas and periods, deterrence from dangerous zones prior to impact). Continuous low-frequency noise is predominantly generated by commercial vessels and recreational boating, with additional contribution from offshore infrastructure (oil and gas, renewables). Mitigation measures are primarily source modification (improving design and operational procedures/speed reduction) and time/area restrictions (including regional/local speed limits and/or requirements for vessels to abide by specific noise emission standards). Additional sources currently not monitored include echosounders and high frequency sonars, net pingers and seal scarers, and equipment other than air guns for exploring the uppermost layers of the seabed (subbottom profiling and surveying).

ISBN: 978-87-7156-780-9
ISSN: 2244-9981