Pelagic fish and harbour porpoise at North Sea wind farms: acoustic investigation and science communication

Demuynck, J.M.

Citation

Demuynck, J. M. (2026, March 13). *Pelagic fish and harbour porpoise at North Sea wind farms: acoustic investigation and science communication*. Retrieved from https://hdl.handle.net/1887/4296692

CHAPTER 1

General introduction

Anthropogenic noise underwater and impacts on aquatic life

1. Anthropogenic noise underwater

The underwater world is inherently full of sound. The aquatic environments of the earth typically contain a multitude of natural sound sources that make up the underwater soundscape, which can be categorised into two distinct types: geophony and biophony. Geophony concerns naturally occurring sounds from non-biological origin, such as earthquakes, weather and hydrothermal vents. Biophony concerns sounds generated by organisms, ranging from whales, coral reef inhabitants, to even photosynthesising plants. However, since recent decades, a third sound source category considerably contributes to the soundscape of not just the terrestrial environment but of the underwater world too: anthrophony (Duarte et al., 2021; Merchant et al., 2022). Man-made sounds are prevalent pollutants in many kinds of aquatic environments, including freshwater systems (rivers and lakes), estuaries, and marine waters (shallow coastal waters, open oceans and the deep sea) (Figure 1). Recently, more studies are therefore focussed on investigating the extent to which anthrophony contributes to the underwater soundscapes, especially in highly exploited areas (e.g. in the Belgian part of the North Sea: Parcerisas et al., 2024), and the effects it may have on aquatic life.

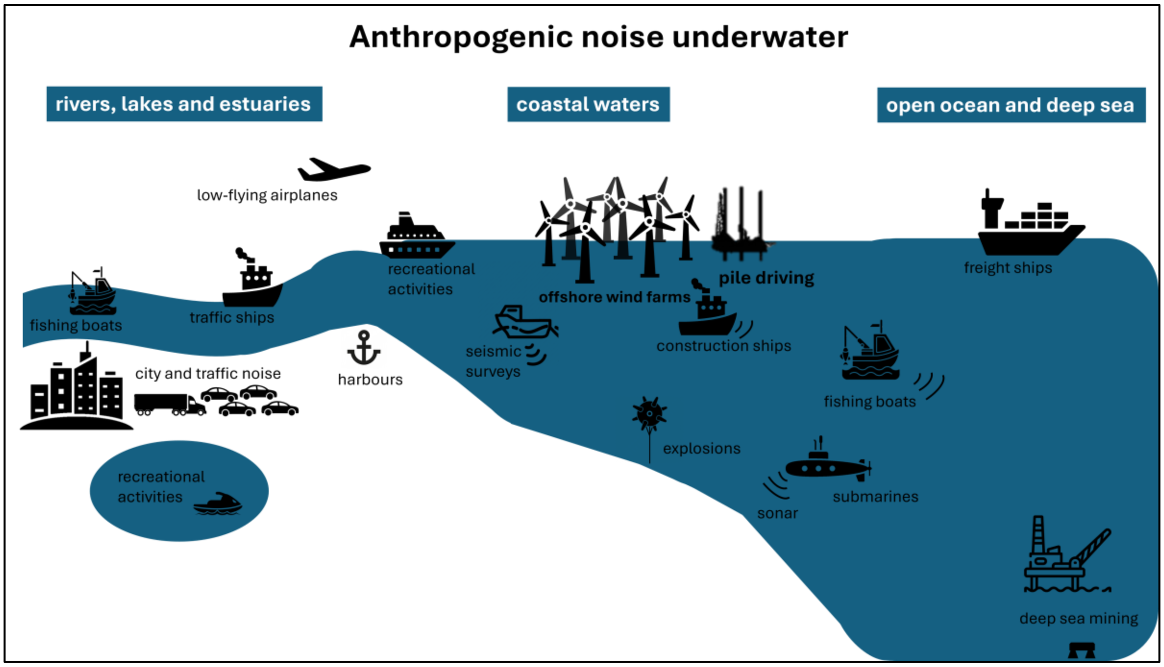

Figure 1: Schematic overview of the most prevalent anthropogenic noise pollution sources to the underwater environment, including freshwater systems (rivers and lakes), estuaries, and marine waters (shallow coastal waters, open oceans and deep sea).

For various human activities, sound is intentionally produced for a certain purpose. For example, sound is used in seismic surveys in order to explore the seabed. An energy source ('air gun') is used to send sound pulses outward, which are then reflected from the sea floor back to the seismic vessel to be picked up by a large number of receivers (hydrophones). Sonar is a similar example of an anthropogenic sound source, where the produced sound has a function: it is used by all vessels at sea and in rivers for depth assessment and navigation, and fishermen often use it for detection of fish schools. Navies across the world also use sonar to communicate and monitor the presence of vessels and submarines (Defence Industries, 2025).

However, many anthropogenic activities also come with unintended sound production; where the sound itself does not have a function but is rather a byproduct of the activity. The most obvious example is the underwater noise produced by ship engines and especially by cavitation from the propellers. Another significant example are offshore wind farms, where the intensity and duration of the noise depends on the stage of production (with high intensity sound pulses during pile driving in the construction phase and low intensity continuous noise during the operational phase). In any case, aquatic animals face significant challenges with the alteration of their acoustic world by the prominent rise in anthropogenic noise (Slabbekoorn et al., 2018).

2. Effects of anthropogenic noise on aquatic life

For many aquatic animals, hearing is an important sensory system for their survival and reproduction, especially during night time and in murky waters where vision provides limited information about the environment. In water, sound travels about five times faster than in air because of the higher molecular density. Additionally, sound also travels farther since wavelengths are longer and attenuate slower in water. For many aquatic species, sound is therefore important for orientation and navigation, as well as communication. In the face of global change, aquatic animals also face multiple other challenges, such as overfishing, rising sea temperatures and habitat degradation. Anthropogenic noise is now also receiving more attention as a pollutant.

Anthropogenic noise can pose a direct threat to aquatic species when it causes them physical harm (Harding & Cousins, 2022), such as temporary or permanent hearing damage, or if it even results in death. This can happen if the acoustic pressure of a sound is so high it ruptures tissue. Seismic surveys, pile driving and explosions are examples of high intensity sounds that can be detrimental to such an extent for nearby animals. Typically, this only concerns those individuals that are relatively close, in the 'danger zone' of the activity. Besides direct physical harm, anthropogenic noise can also impact animals indirectly (Harding & Cousins, 2022), affecting a more substantial amount of animals and across a larger area farther away from the sound source. This can happen if the sound source has spectral overlap with the animals' hearing range (Figure 2), and the temporal pattern, familiarity and predictability of the sound will determine the extent of its impact.

Anthropogenic noise can indirectly impact the fitness of animals through disturbance, deterrence, distraction, or masking. (1) Disturbance can occur if a behaviour important for the animals' reproduction and survival is interrupted. For example, free-ranging Atlantic cod (*Gadus morhua*) showed a disrupted diurnal cycle during a seismic survey, with reduced activities at dusk and dawn when they are usually actively feeding (Van Der Knaap et al., 2021). (2) Deterrence by anthropogenic noise causes animals' to flee a potentially suitable habitat. For example, harbour porpoise (*Phocoena phocoena*) has been shown to flee the construction site of an offshore wind farm for up to 12 km during piling and other construction work (Benhemma-Le Gall et al., 2021). Even a delayed displacement may occur, for example the free-ranging cod in the seismic survey study were leaving the area more quickly than expected from 2 days to up to 2 weeks after the survey (Van Der Knaap et al., 2021). Reduced feeding or mating opportunities can thus be a consequence of the animals deserting a potentially suitable habitat due to anthropogenic noise. (3) Anthropogenic noise can also be distracting to animals, which may have consequences for their survival as well. For example, in an experimental setting, Caribbean hermit crabs (*Coenobita clypeatus*) were later in hiding for a looming predator when exposed to boat noise, indicating the sound may impact their risk-assessment (Chan et al., 2010). This could have be due to distraction, or due to the predator's sound being less easily detectable (the latter also called masking, see further). However, in this study, they found the same result even with a silent simulated predator, and when flashing lights were added to the boat noise the hermit crabs were even later in hiding, further supporting the distraction hypothesis (Chan et al., 2010). (4) Finally, masking can occur when anthropogenic noise causes important acoustic cues to be drowned out. For example, decreasing foraging efficiency was observed in fish-eating killer whales (*Orcinus orca*) with increasing vessel noise, suggesting auditory masking of their biosonar-based hunting behaviour (Tennessen et al., 2024).

The hearing ranges of many aquatic animals overlap with the frequencies of various sources of anthropogenic noise (Figure 2). Fish can typically hear in the lower frequency ranges (up to a few hundred Hz), while marine mammals usually hear much higher frequencies (up to over a hundred kHz). Invertebrates can also detect and use sound, although they are often restricted to even lower ranges than fishes, and may therefore be impacted by anthropogenic noise as well. Finally, many bird species forage at sea for fish or invertebrates in the bottom, and their hearing may be less than when in air, but they are like the other taxonomic groups likely affected by anthropogenic noise through disturbance, deterrence, distraction, or masking. It is interesting to mention that while fish and invertebrates hear the particle motion component of sound and only sound pressure when they have a gas-filled cavity such as a swim bladder, birds and marine mammals predominantly hear by sound pressure and thereby have to rely on two ears for directional information. With ever-increasing human activities, understanding how anthropogenic noise impacts life under water is important for the welfare of populations, communities, and the whole ecosystem.

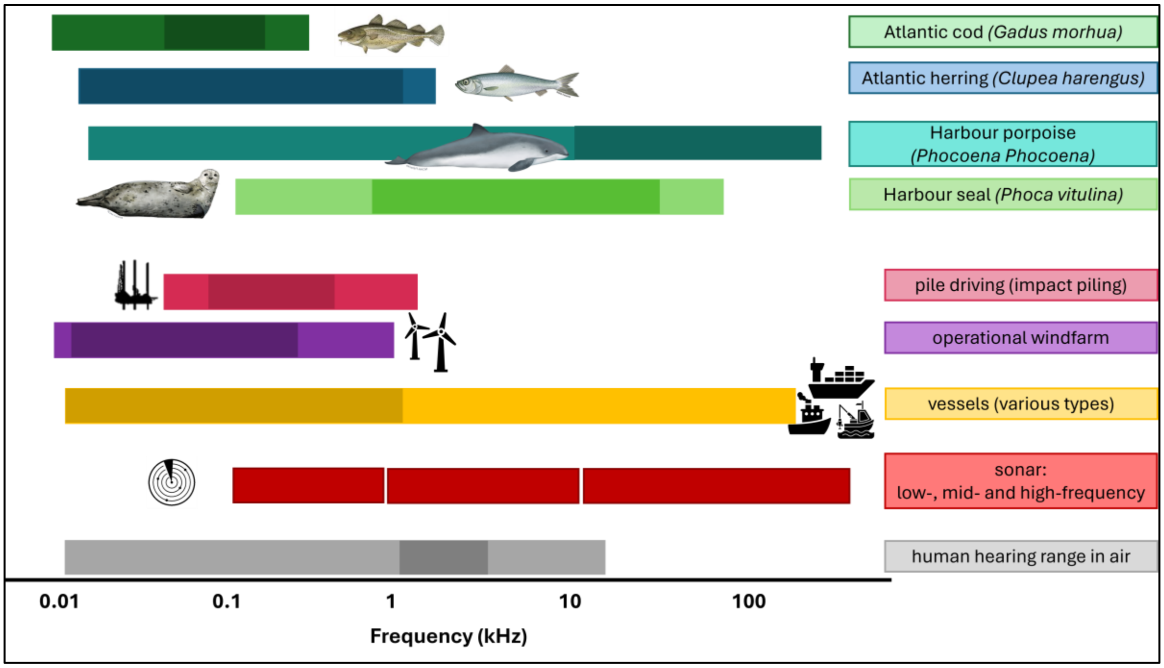

Figure 2[1]**:** Schematic overview of approximate hearing ranges of some species commonly found in the North Sea (and human hearing for comparison), and frequency ranges of some prevalent anthropogenic noise sources. Darker boxes inside frequency ranges indicate: for species where highest sensitivity of hearing lies, and for sound sources where most of the energy lies. Note that the 'vessels (various)' category spans a broad frequency band due to the diversity of vessel types and sizes (typically smaller vessels radiate noise at higher frequencies but with less energy than larger ships).

Offshore wind farms and effects on marine life

In this thesis, the focus of anthropogenic noise effects on aquatic life was for the most part in relation to offshore wind farms and pelagic fish. Currently, Europe has more than a hundred active offshore wind farms for a total capacity of over 30 GW across 13 countries (WindEurope, 2025). The studies from this thesis are conducted in the wind farm area at the Dutch-Belgian border (Figure 3) that have a combined capacity of roughly 3.5 GW. In order to reach the EU's renewable energy and climate targets, the capacity of offshore wind energy is still ever increasing. For the whole of the North Sea basin, the ambition of at least 300 GW of installed capacity by 2050 was set in the Ostend Summit in 2023 (European Commission, 2023). The most recently installed turbines are usually larger with increased capacity, and also other renewable energy methods are being introduced at sea (such as

---

[1] Literature list for Figure 2: Main figure adapted from Slabbekoorn et al. (2010); Atlantic herring hearing (Enger, 1967); Atlantic cod hearing (Chapman & Hawkins, 1973); Harbour seal hearing (Hamilton, 1957); Pile driving (impact piling) sound (Matuschek & Betke, 2009; Norro et al., 2010; Robinson et al., 2013); Operational wind farm sound (Marmo et al., 2013; Yoon et al., 2023); Vessel sounds (various) (Veirs et al., 2016); Sonar sounds (DOSITS, 2002-2005; Slabbekoorn et al., 2010).

floating wind farms, tidal energy lagoons or floating solar panel fields). As increasingly more offshore wind farms are being built, research has also been growing in the past decade focused on investigating potential short- and long-term effects on the marine environment.

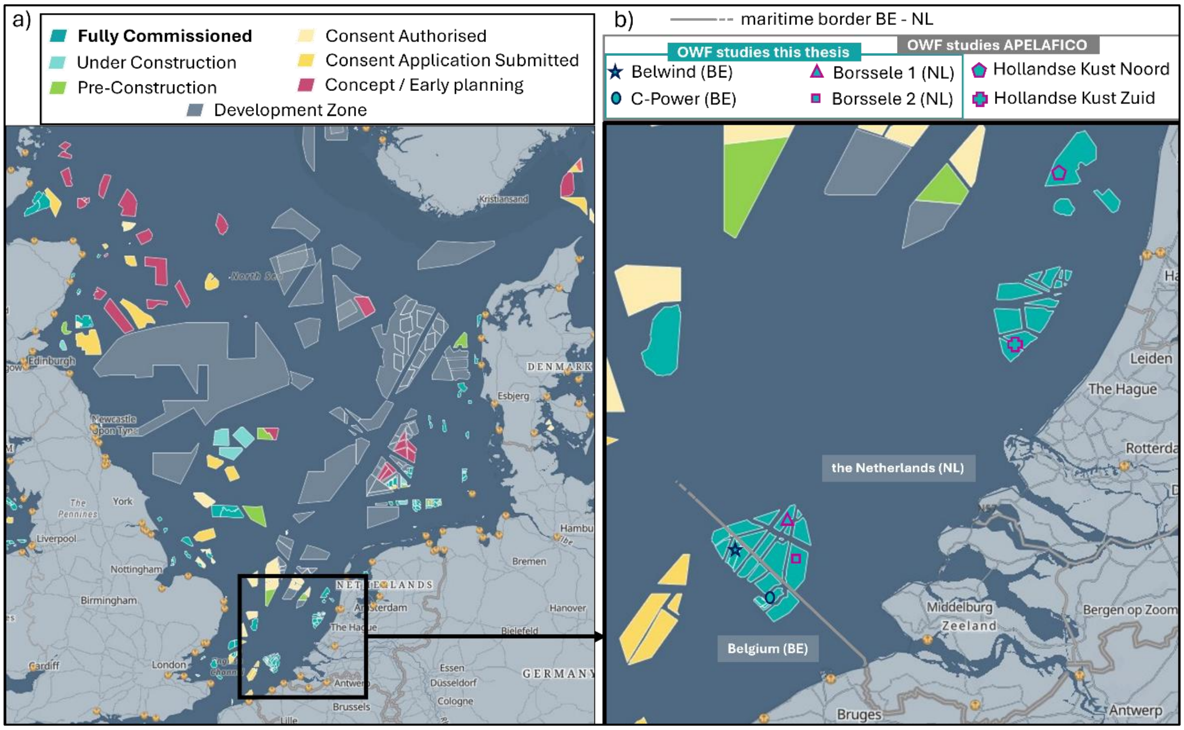

Figure 3: a) Map of current and planned offshore wind parks in the North Sea, as of writing this thesis (2025), from https://map.4coffshore.com/offshorewind/. b) Zoom in on the wind parks at the Dutch-Belgian border, where studies were conducted as part of this thesis, and for the APELAFICO project as a whole.

As their name suggests, pelagic fish inhabit primarily the pelagic zone of the water column (away from the bottom) and often form schools (NOAA, 2024). Pelagic fish are a taxonomic group of fish with both ecological (Palomera et al., 2007; Stephenson & Smedbol, 2019) and economical (Stephenson & Smedbol, 2019; Toresen & Østvedt, 2008) importance. For example, small pelagic fishes specifically are a key link in the food chain of the marine ecosystem, as by feeding on plankton they transfer nutrients from low to high trophic levels (Greenstreet, 1997; Cury et al., 2000; Murphy et al., 2016). Pelagic fish are also the target of intensive fishing activities; for example herring are in the top ten most fished species (FAO, 2022).

1. Offshore wind farms change the local marine habitat

Offshore wind farms can directly impact the surrounding marine habitat of animals by physical alterations to the environment caused by the turbines in various ways. (1) Water currents are locally altered around the turbines and cause turbulent ‘wakes’ which can change the stratification of the water column (Carpenter et al., 2016), which in turn can impact primary production (Daewel et al., 2022). (2) The subsea power cables generate anthropogenic Electro-Magnetic Fields (EMFs) that can have effects on those species that rely on natural EMFs as ecological cues (Hutchison et al., 2020; Öhman et al., 2007), such as sharks and rays (elasmobranchs). For example, various laboratory studies indicate an impact of EMFs on the early life development of fish (Svendsen et al., 2022). The observed behavioural changes in-situ for various species groups seem minimal so far, yet long-term effects are still understudied (Bilinski, 2021). (3) Wind farms also significantly alter the local structure of the sea floor with scour beds that should protect the area around the turbines from scour or erosion (i.e. the local displacement of sand or soil due to strong water currents around the turbine), as well as the introduction of the turbine itself. Since extensive bottom-trawling has reduced most of the naturally occurring hard substrates on the seabed in the North Sea, newly introduced structures of offshore wind farms actually provide a suitable habitat for various species. For example, a higher epibenthic biodiversity has been observed in the North Sea around scour protection of turbines compared to the surrounding sandy seabed (Ter Hofstede et al., 2022). The amount and kind of fish species attracted to structures of offshore wind farms depends on the type of turbines, foundations and the sites (Bicknell et al., 2025). A local biodiversity increase of hard-substrate species around man-made structures is often called an 'artificial reef effect'. The artificial reef effect of offshore wind farms can change the local ecosystem structure and functioning (Degraer et al., 2020).

The changes in local habitat-structure and artificial reef effects on hard-substrate species will also affect other species and species interactions, although we still know much less about long-term knock-on effects. Colonizing hard-substrate species, also called 'fouling' species, are attracted first by artificial reefs (Degraer et al., 2020). Typically, mussels (e.g. the blue mussel, *Mytilus edulis*), barnacles and macroalgae are found on the hard substrate close to the water surface, while filter-feeding arthropods and anemones (e.g. plumose anemone, *Metridium senile*) are found further down the water column (De Mesel et al., 2015). These hard-substrate species can then provide local organic enrichment by their faeces (Degraer et al., 2020). Larger mobile species can in turn be attracted by the biofouling community and the hard substrate, such as crabs and lobsters (Krone et al., 2017). Hard-substrate-preferring fish species can also increase in abundance near the structures, such as cod, pouting (*Trisopterus luscus*) or bulltrout (*Myoxocephalus scorpius*) (Van Hal et al., 2017) and increased fish species diversity has indeed been observed closer to turbines (Stenberg et al., 2015). The top predators could in turn also be attracted to these sites. For example, harbour seals have been observed through GPS tracking to move from turbine to turbine (McConnell et al., 2012).

For those species that are less bound to the sea floor, such as pelagic fish, it is still unclear what the longer-term impact of the change in environment due to offshore wind farm structures will be. Pelagic fish could be affected negatively, considering the potential impact of pile driving noise and the change in open habitat structure. In turn, the predators of pelagic fish can be impacted as well. On the other hand, effects of offshore wind farms may be neutral for pelagic fish, if the nature of the species is to readily respond to changing food or predator conditions by moving to more suitable areas. A positive effect may be possible as well, by higher food densities due to the artificial reef effect, and a potential refuge-effect due to restricted fishing in offshore wind farm areas.

2. Noise pollution from offshore wind farms

1.1. Preparatory stage

During the process of offshore wind farm construction and operation, different types and intensities of sound are produced (Figure 3). Prior to construction of an offshore wind farm, seismic surveys are conducted to map the structure of the seabed and find a suitable location. Sound pulses from seismic surveys are typically high in intensity and can impact the behaviour and physiology of marine animals. There are different seismic survey methods using different frequency ranges of different sound sources (Schuck & Lange, 2007), which may impact different species depending on the overlap with the hearing range. So far most studies only focussed on the effects on marine mammals, while research on other taxa is largely lacking (Affatati & Camerlenghi, 2023). When a suitable location is determined, local preparatory work is carried out before the actual pile driving starts. This stage of preparation is typically accompanied by vessel noise, which can also disturb and deter animals. For example, a short-term effect on harbour porpoise distribution has been shown as animals avoided areas of high vessel density for up to 9 km (Pigeault et al., 2024), while some bird species diving for fish are reported to largely abandon wind farm areas after the establishment of the parks (e.g. loons: Garthe et al., 2023).

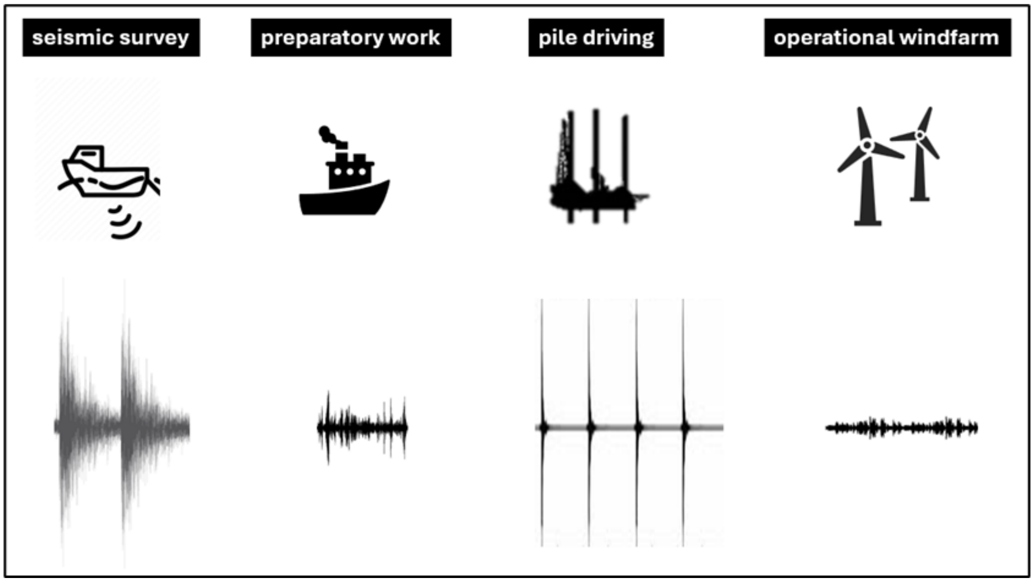

Figure 4: Schematic representation of different types noise production during different stages of offshore wind farm construction and operation. Note that seismic surveys and pile driving are more intense and impulsive, while vessel noise and operational turbines are lower in intensity and continuous.

1.2. Construction stage

During the actual construction of the wind farm, the turbines are individually driven into the seafloor by means of pile driving. Impact piling is the most common method of pile driving, where the large turbine monopile (recent turbines typically have a diameter of up to 8 m) is hammered into the seabed with a hydraulic hammer, which comes with high intensity sound pulses under water (Tsouvalas & Metrikine, 2016). Alternative methods to impact piling include vibratory piling, in which vibration is used to drive the turbine into the seafloor instead of hammering. While vibratory piling comes with continuous rather than intense impulsive noise, the method is generally less effective for precise and deep seabed penetration in challenging soil conditions compared to impact piling (Massarsch et al., 2017). To mitigate the intensity of the sound that comes with impact piling, so-called 'bubble curtains' can be placed around the pile driving site (Bohne et al., 2019). A vessel is used to pump air through a perforated tube on the sea floor which allows the release of bubbles in one or two rings, resulting in attenuation of the intensity of the sound radiating into the surrounding sea. In one case study as an example, two rings of bubble curtains reduced the sound level of pile driving by around 12 dB when used together (and 7 to 10 dB each when used separately), with attenuation most pronounced for frequencies above 1 kHz. Consequently, this significantly reduced the scale of temporary habitat loss for harbour porpoises (Dähne et al., 2017).

1.3. Mitigation: acoustic deterrence

In the context of the loud sounds associated with pile driving for offshore wind farms, another form of mitigation that has come into view is acoustic deterrence. An acoustic deterrent device (ADD) plays back sounds at safe levels to deter animals away from an area, to prevent future harm from anthropogenic activities (such as pile driving noise), and/or to guide them to a more favourable area. Currently, most ADDs used at sea are targeted towards marine mammals. For example, the porpoise module of the 'FaunaGuard' (developed by SEAMARCO and Van Oord Dredging and Marine Contractors, currently on the market via Ace Aquatec) has been shown effective in deterring harbour porpoises from construction sites to prevent hearing damage (captive study: Geelhoed et al., 2017; field study: Voss et al., 2023). Also at fish farms, for example, 'seal scarers' can be used to prevent predation (Götz & Janik, 2013).

Deterrent devices for fish have also been developed for various purposes with varying success depending on the target species (Wahlberg 1999; Putland & Mensinger, 2019). At a cooling water inlet of a nuclear powerplant in Belgium, the use of sound playback at 20–600 Hz proved effective in reducing the number of trapped sprat (*Sprattus sprattus*) and Atlantic herring (*Clupea harengus*) (Maes et al., 2004). For freshwater migrating fish, ADDs can be used for redirection to more favourable routes, such as shown for European silver eels with infrasound (Sand et al., 2000). However, less is known about which sounds could be effective to deter pelagic fish at sea from construction sites such as pile driving. For example, the sounds used in an early fish module of the FaunaGuard did not elicit any response in European seabass in a captive test (Research Report Wageningen University & Research and Leiden University: Hubert & Neo, 2017). More insight is therefore needed into the response of pelagic fish and other less-studied taxonomic groups to sounds of moderate level as potential for acoustic deterrence.

1.4. Captive and field studies

Insights into the role of sound for fish in the natural environment can come from complementary studies on captive individuals in the lab, as well as from observation on free-ranging individuals in the field (Slabbekoorn, 2016). In the lab, dedicated experimental aquarium set-ups can provide a controlled environment to look at details in behavioural responses to sounds of interest. For example, Atlantic cod in an experimental basin increased their time spent swimming and decreased their time remaining stationary on days with seismic survey sound exposures of moderate level compared to days without (Hubert, Wille, et al., 2020). In another example, pile driving playbacks have been shown to disrupt the structure and dynamics of shoals in juvenile seabass (*Dicentrarchus labrax*) in captivity (Herbert-Read et al., 2017). Captive individuals can also be studied in a more natural setup, such as with outdoor floating pens, where the natural light-dark and tidal cycles occur, and where acoustic conditions concern a natural situation (Slabbekoorn 2016). In such a set-up, European seabass (*Dicentrarchus labrax*) have similar patterns of acoustic responsiveness compared to earlier indoor studies on this species (Hubert, et al., 2020) and have for example been shown to increase their swimming speed, depth, and group cohesion in response to impulsive sound playback, and they did so more strongly at night (Neo et al., 2018).

However, to understand the impact of anthropogenic noise in-situ, complementary studies of free-ranging individuals in the field are also important. Controlled exposure conditions and detailed observations can be more challenging due to unpredictable or unfavourable outdoor conditions (murky waters, bad weather conditions, and larger spatial range). Still, tagging and echosounders (Figure 5) can provide a way to look at the behaviour of fish schools and even track individual fish in the field (Kok et al., 2021; Van Der Knaap et al., 2021a). For example, tagged free-ranging Atlantic cod were tracked around windmills and changes to their behaviour could be observed during and after a seismic survey (Van Der Knaap et al., 2021b). During pile driving activity, echosounders allowed researchers to observe that free-ranging fish swam closer to the scour bed of the nearest windmill during piling, and they moved a bit further away from the source direction, after having moved a bit closer in the preceding period (van der Knaap et al., 2022). Hence, both captive studies for detailed behavioural patterns and field studies for in-situ responses can be valuable to understand the extent of impact of anthropogenic noise on fish.

Figure 5: Picture during deployment of monitoring sensors for a study as part of this thesis. This frame was designed by LifeWatch and the Flanders Marine Institute (VLIZ) and allowed for multiple sensors to be deployed at once. The yellow cylinder mounted horizontally is an echosounder that allows tracking of free-ranging fish. The grey cylinder mounted vertically is a C-POD that records the vocalisations made by harbour porpoise (*Phocoena phocoena*). This fieldwork picture was taken from the Belgian research vessel Simon Stevin.

Public awareness on the effects of anthropogenic noise on marine animals

1. Awareness of impact of anthropogenic noise on aquatic life

1.1. Aquatic animals and sound

The importance of sound to aquatic animals has long been underestimated and understudied, which probably has several reasons. First, most aquatic animals are not regularly encountered in their natural environment by most people, which is especially the case for marine species. This limited encounter rate with aquatic animals could make it more challenging to learn about them and to be aware of any challenges they might face. Second, underwater sound seems unnoticeable or far away for us since sound does not travel well from water to air. Even if we put our heads underwater, we lose a significant part of our hearing ability (Brandt & Hollien, 1967) and we are typically more focused on what we see (e.g. while snorkelling). Additionally, anthropogenic noise from boats or diving equipment can locally drown out most of the natural sounds present. Lastly, the hearing abilities of aquatic animals are considerably different from ours, especially of fishes and invertebrates. As humans, we rely on sound pressure for hearing, like marine mammals, whereas all other aquatic animals also make use of the particle motion aspect of sound to extract information from the environment about a sound source under water (Nedelec et al., 2016; Popper & Hawkins, 2018). This makes taking an animals' perspective of the acoustic underwater world even more challenging. However, recently more attention has been given to the importance of sound for aquatic animals and thereby also to the potential disruption of the environment by anthropogenic noise (Duarte et al., 2021; Merchant et al., 2022; Williams et al., 2015).

1.2. Research and policy

Most likely one of the first events that indicated that sounds from human activities may disturb aquatic animals was the observed patterns in marine mammal strandings. For example, increasing concern was raised on correlations between worldwide mass strandings of beaked whales and concurrent naval exercises and sonar (Cox et al., 2006). These kinds of events and consequential concerns have since kickstarted numerous research studies as well as changes in policy laws and guidelines. However, specific guidelines to underwater noise limits are often still lacking and much research is still needed on direct or indirect impacts of anthropogenic noise on aquatic life (Faulkner et al., 2018; Hawkins et al., 2015; Merchant et al., 2022; Southall et al., 2019).

In the European 'Marine Strategy Framework Directive' (MSFD), a guide for underwater noise regulations is provided and member states should aim to achieve 'Good Environmental Status' (GES) (European Parliament and Council, 2008). However, the MSFD does not suggest any specific limits of noise pollution levels, so limits to the intensity of underwater sound are typically set at country level. For example, a limit of 160 dB re 1 μPa sound exposure level (SEL) and 190 dB peak-to-peak for pile driving was set by German authorities (Müller & Zerbs, 2011). Belgium set the limit at a maximum zero-to-peak noise level of 185 dB re 1 µPa at 750 meters from the source (Rumes et al., 2013), whereas the Netherlands have not adopted a fixed limit but rather evaluate the acoustic impacts case-by-case (LEI Performance and Impact Agrosectors et al., 2018). These limits are usually only set with the protection of marine mammals in mind, especially the noise pollution sensitive harbour porpoise. Guidelines for fishes and invertebrates are often still lacking, which is most likely related to the fact that impacts of anthropogenic noise on these groups have been less studied (Hawkins et al., 2015, 2020; Hawkins & Popper, 2017). However, many fish species are important to our economy, and they play, along with many invertebrate species, a key role in the ecological food-chain. More fundamental research is still needed to understand the extent of the impact of anthropogenic activities on all aquatic life, as well as applied studies with value to policy makers in order to mitigate any adverse effects as much as possible.

1.3. Importance of science communication

For experts it is important to readily share the results of their studies and the applied consequences of their findings with stakeholders in ministries, fisheries, conservation agencies and any other involved companies (e.g. offshore wind farm companies). However, the general public is also a key group to be involved in the issue of anthropogenic noise pollution. Many economically important fish species (such as for the food industry) could be negatively impacted by anthropogenic noise, so their well-being is indirectly linked to ours. If the general public has a better understanding of the issue of anthropogenic noise pollution, it can create a sense of responsibility towards the affected animals. Indirectly, the general public could help change things for the better through influencing companies and policymakers, or by supporting conservation agencies. For example, a study using a large-scale survey on public awareness showed that the level of their concern for anthropogenic impacts on the marine environment was closely associated with the level of their 'informedness' on the matter (Gelcich et al., 2014). Since the general public most often still lacks knowledge on the extent of anthropogenic noise impact on aquatic animals, experts should also engage in outreach activities targeted to this group.

1.4. The APELAFICO project and public engagement

The empirical studies described in this thesis were part of the 'APELAFICO' project. APELAFICO is short for 'Acoustic Ecology of Pelagic Fish Communities' and the project focussed on the effects of sounds from construction and operation of wind farms in the North Sea on pelagic fish and a prominent predator, the harbour porpoise. The project had three main goals: (1) to test new potentially deterring sounds to improve current fish ADDs, (2) to monitor the presence and behaviour of pelagic fish near pile driving, and (3) to monitor the presence and behaviour of pelagic fish and harbour porpoise in operational wind farms. As part of the Dutch Research Agenda (NWA) and the Dutch Governmental Offshore Wind Ecological Program (WOZEP), the project was funded by the Dutch Research Council (NWO), with complementary funding from Rijkswaterstaat (the executive agency of the Dutch ministry of infrastructure and water management). Many partners and stakeholders were part of the program (Figure 6), of which the main three were the Institute of Biology Leiden (IBL) of Leiden University, the Flanders Marine Institute (in Dutch: VLIZ, Vlaams Instituut voor de Zee) and Wageningen Marine Research (WMR), IJmuiden.

Figure 6: Funding, partners and stakeholders of the APELAFICO project. (1) Funding: Dutch Research Council (NWO) and Dutch Research Agenda (NWA). Dutch government: the Dutch Governmental Offshore Wind Ecological Programme (WOZEP) and the Ministry of Infrastructure and Water Management (Rijkswaterstaat). (2) Main partners: Institute of Biology Leiden of Leiden University, Flanders Marine Institute (VLIZ) and Wageningen University. (3) Stakeholders: Institute of Marine Research (IMR), Otary Offshore Energy, IQIP on- and offshore foundation and installation, Van Oord, Stichting De Noordzee, Gemini Wind Park, Vattenfall Wind Park, Dutch Organisation for Applied Scientific Research (TNO), Stichting Vissenbescherming, Pelagic Freeze Trawler Association (PFA), JASCO Applied Sciences, Royal Belgian Institute of Natural Sciences (RBINS).

At the end of the project, a closing event was held at the Blijdorp Rotterdam Zoo (Figure 7). The symposium was split in two parts: in the morning, groups of high-school students were invited, and the afternoon was open to partners, stakeholders and their invitees. In each part of the program, three talks were given, tailored to the audience: on sound under water, on how to evoke behavioural change in humans, and on the main results of the APELAFICO project. After the talks, an 'acoustic tour' was provided through the Oceanium facility, where explanations were given at various species on how sound is important in their everyday life. For the morning program, the main goal was to introduce young students to the acoustic underwater world and the potential impacts of anthropogenic noise on marine animals. In total, over 70 students and teachers attended the symposium. For the afternoon program, partners and stakeholders were each encouraged to invite colleague, friend, or family which was not familiar with the research topic of the project. The goal was not only to wrap up the three-year project with the stakeholders, but also to reach out to a larger audience and give a broad introduction and overview of the discipline for the invited non-experts. As another outreach effort, I also explained the fundamental and applied insights in a YouTube video, made in collaboration with 'de Universiteit van Nederland', on the effects of offshore wind farms on fish (Figure 8; https://youtu.be/xGjTqCFPZto?si=4SpsBigRLowSvzBr). The target audience of this video was the general public interested to learn more about the topic.

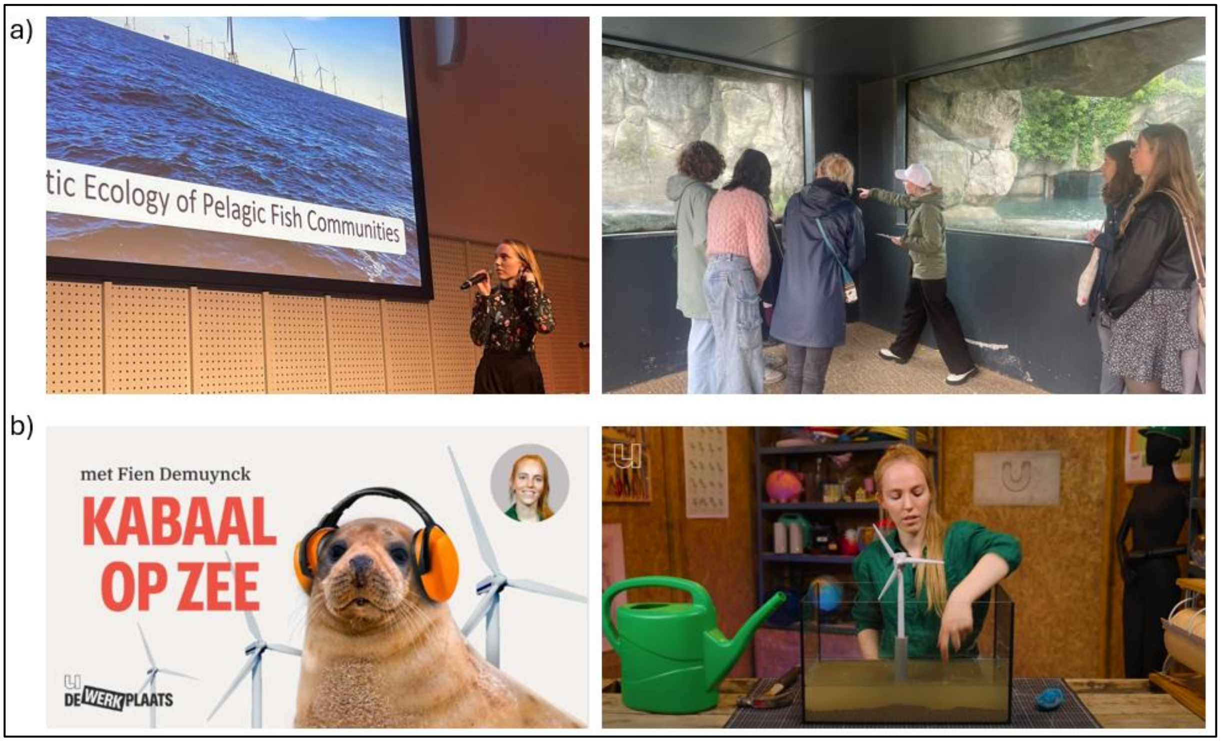

Figure 7: Public engagement during my PhD: a) Pictures from the APELAFICO closing event at Blijdorp Rotterdam Zoo during the talk program (left) and the acoustic tour (right). b) Thumbnail (left) and picture (right) of YouTube video in collaboration with de Universiteit van Nederland.

2. Research in science communication

Given the importance of informing the general public about research and policy outputs of the APELAFICO project, science communication (SciCom) became core to this thesis. Horst, Davies and Irwin (2016) suggested the following definition for SciCom: 'organized, explicit, and intended actions that aim to communicate scientific knowledge, methodology, processes, or practices in settings where non-scientists are a recognized part of the audiences'. In order to effectively communicate scientific insights to stakeholders, policy makers, companies or the general public, an appropriate method should be used to reach the target audience, and studying this is a research field on its own. With more than 50 years of research, the SciCom research field provides theoretical frameworks and empirical evidence to improve our knowledge on best practices for effectively communicating scientific findings to non-experts (Guenther & Joubert, 2017). The research field involves quite a large variety of studies, with typically an interdisciplinary nature. For example during the Covid pandemic, research in health communication included studies on the spread of misinformation and distrust in public health institutions (Public Health Ontario, 2023). Special research topics further include, among others, risk communication, science education, and environmental communication.

Locations where the general public comes in close contact with animals are zoos and public aquariums. Zoos and public aquariums provide not just entertainment to the public, but also an opportunity for education (Colléony et al., 2017; Karydis, 2011). Animals in zoos and public aquariums are also regularly exposed to noisy conditions from surrounding cities, construction inside or nearby the exhibit, or by visitors themselves, which may impact behaviour, physiology, and well-fare of animals (Jakob-Hoff et al., 2019; Kleinberger, 2023; Kratochvil & Schwammer, 1997; Lewis et al., 2024; Orban et al., 2017; Pelletier et al., 2020; Quadros et al., 2014) as well as appraisal and well-being of humans (Rice et al., 2021, 2024). These locations therefore provide an excellent opportunity to communicate about and educate on the impacts of man-made noise on animals. The management tools to reduce visitor noise in zoos and public aquaria, for the sake of animals and fellow visitors, is worth to study in itself and one way to insert acoustic education about the world of natural sounds and noise pollution to the general public.

Thesis outline

This thesis consists of a general introduction (chapter 1), five research chapters (Figure 8), and a general discussion (chapter 7).

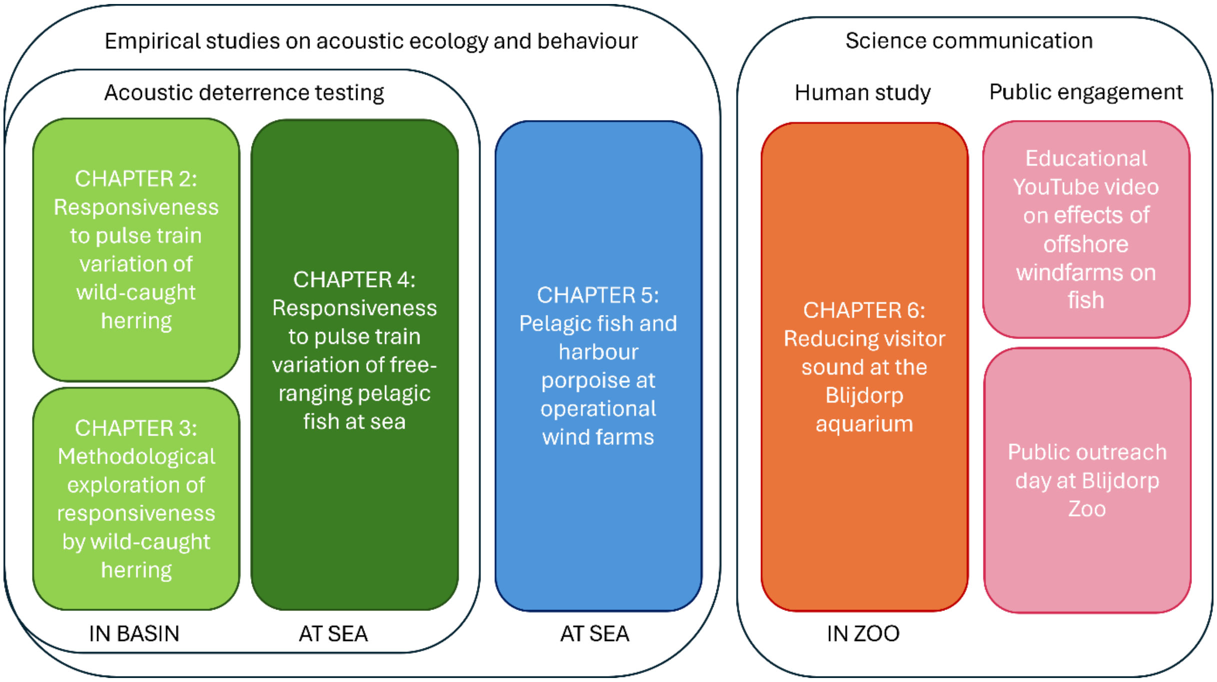

Figure 8: Overview of the five research chapters in this thesis and public engagement activities.

In chapters two and three, I report about the basin study during which I tested acoustic stimuli on wild-caught Atlantic herring. One of the goals of the APELAFICO project was to study the potential for using sound as a deterrent for fish to herd them away from acoustically dangerous sites of extreme overexposure. The herring were exposed to a set of acoustic stimuli designed based on a ‘looming sound’ hypothesis, and their behaviour was observed with underwater cameras and tracked with a tracking program. The overall research question for this study was the following: ‘does a looming sound stimulus evoke a behavioural response in herring in captivity, indicative of potential applicability as acoustic deterrent at sea?’ In chapter two, I report on the main results of this study, while chapter three then focuses on the methodological part of the study and the persistence of herring’s responsiveness over time.

In chapter four, the results of the follow-up experimental exposure study at sea are reported. Similar varying pulse train sound stimuli were tested as in the basin study, as well as up-sweeps stimuli. This time the test was done on free-ranging fish in the North Sea, and echosounders were used to monitor pelagic fish presence and behaviour during exposure to the sound stimuli. The overall research question for this study was the following: ‘do free-ranging fish flee from various sound stimuli meant as acoustic deterrents?’.

In chapter five, I report on a study in which pelagic fish and harbour porpoise were monitored in offshore wind farms, as well as measurements on ambient sound levels. Echosounders were used to detect pelagic fish, C-PODs for the recording of harbour porpoise vocalisations, and hydrophones for measuring ambient sound levels. As a control for the offshore wind parks, simultaneous measurements were done at shipwrecks, resulting in pairwise sampling. The overall research question for this study was the following: 'how are pelagic fish abundance, harbour porpoise presence and ambient sound levels different in OWFs compared to outside OWFs?'.

In chapter six, a study in context of human noise and fish welfare is described, this time with the focus on human behaviour rather than animal behaviour. This final study was indeed different in topic than the previous studies of this thesis, while still falling under a broader anthropogenic noise context. After the three-year APELAFICO project, this final study as part of this thesis was conducted in collaboration with the Science Communication and Society research group (SCS) of the IBL. The study took part in the Blijdorp Rotterdam zoo and was focused on improving communication towards visitors to reduce their sound production (talking and screaming), hoping to benefit the visitor experience and animal welfare at the aquarium. In the Oceanium facility, different signs and an audio message were tested for their effectiveness to reduce visitor sound levels. To measure the impact of the different treatments, I measured sound levels and conducted visitor surveys. The overall research question for this study was the following: 'how do visitors experience noise at the aquarium and can visitor sound levels be lowered using signage?'.

In the final chapter, the findings from each of the research chapters are summarized and follow-up research is suggested in a general discussion, ending with an overall conclusion.

References

Affatati, A., & Camerlenghi, A. (2023). Effects of marine seismic surveys on free-ranging fauna: A systematic literature review. *Frontiers in Marine Science*, *10*, 1222523. https://doi.org/10.3389/fmars.2023.1222523

Benhemma-Le Gall, A., Graham, I. M., Merchant, N. D., & Thompson, P. M. (2021). Broad-Scale Responses of Harbor Porpoises to Pile-Driving and Vessel Activities During Offshore Wind farm Construction. *Frontiers in Marine Science*, *8*, 664724. https://doi.org/10.3389/fmars.2021.664724

Bicknell, A. W. J., Gierhart, S., & Witt, M. J. (2025). Site and species dependent effects of offshore wind farms on fish populations. *Marine Environmental Research*, *205*, 106977. https://doi.org/10.1016/j.marenvres.2025.106977

Bilinski, J. (2021). Review of the Impacts to Marine Fauna from Electromagnetic Frequencies (EMF) Generated by Energy Transmitted through Undersea Electric Transmission Cables. *Report New Jersey Department of Environmental Protection – Division of Science and Research.*

Bohne, T., Grießmann, T., & Rolfes, R. (2019). Modeling the noise mitigation of a bubble curtain. *The Journal of the Acoustical Society of America*, *146*(4), 2212-2223. https://doi.org/10.1121/1.5126698

Brandt, J. F., & Hollien, H. (1967). Underwater Hearing Thresholds in Man. *The Journal of the Acoustical Society of America*, *42*(5), 966-971. https://doi.org/10.1121/1.1910704

Carpenter, J. R., Merckelbach, L., Callies, U., Clark, S., Gaslikova, L., & Baschek, B. (2016). Potential Impacts of Offshore Wind Farms on North Sea Stratification. *PLOS ONE*, *11*(8), e0160830. https://doi.org/10.1371/journal.pone.0160830

Chan, A. A. Y.-H., Giraldo-Perez, P., Smith, S., & Blumstein, D. T. (2010). Anthropogenic noise affects risk assessment and attention: The distracted prey hypothesis. *Biology Letters*, *6*(4), 458-461. https://doi.org/10.1098/rsbl.2009.1081

Chapman, C. J., & Hawkins, A. D. (1973). A field study of hearing in the cod, *Gadus morhua L. Journal of Comparative Physiology*, *85*(2), 147-167. https://doi.org/10.1007/bf00696473

Colléony, A., Martin, L., Misdariis, N., Clayton, S., Saint Jalme, M., & Prévot, A.-C. (2017). Exoticism as a Mediator of Everyday Experiences of Nature: An Anthropological Exploration of Soundscape in Zoos. *Human Ecology*, *45*(5), 673-682. https://doi.org/10.1007/s10745-017-9937-y

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernandez, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., … Benner, L. (2006). Understanding the impacts of anthropogenic sound on beaked whales. *J. Cetacean Res. Manage.*, *7*(3), 177-187. https://doi.org/10.47536/jcrm.v7i3.729

Daewel, U., Akhtar, N., Christiansen, N., & Schrum, C. (2022). Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. *Communications Earth & Environment*, *3*(1), 292. https://doi.org/10.1038/s43247-022-00625-0

Dähne, M., Tougaard, J., Carstensen, J., Rose, A., & Nabe-Nielsen, J. (2017). Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. *Marine Ecology Progress Series*, *580*, 221-237. https://doi.org/10.3354/meps12257

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., & Degraer, S. (2015). Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. *Hydrobiologia*, *756*(1), 37-50. https://doi.org/10.1007/s10750-014-2157-1

Defence Industries. (2025). Sonar Systems Used by Navies Around the World: Types & Technologies. https://www.defence-industries.com/articles/types-of-sonar-systems-used-by-navies-around-the-world

Degraer, S., Carey, D., Coolen, J., Hutchison, Z., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore Wind Farm Artificial Reefs Affect Ecosystem Structure and Functioning: A Synthesis. *Oceanography*, *33*(4), 48-57. https://doi.org/10.5670/oceanog.2020.405

DOSITS. (2002, 2025). *Sonar*. Discovery of Sound in the Sea. https://dosits.org/animals/effects-of-sound/anthropogenic-sources/sonar/

Duarte, C. M., et al. (2021). The soundscape of the Anthropocene ocean. *Science*, *371*(6529), eaba4658. https://doi.org/10.1126/science.aba4658

Enger, P. S. (1967). Hearing in herring. *Comparative Biochemistry and Physiology*, *22*(2), 527-538. https://doi.org/10.1016/0010-406x(67)90615-9

European Commission. (2023). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. *Delivering on the EU offshore renewable energy ambitions*. COM(2023) 668.

European Parliament and Council. (2008). Directive 2008/56/EC of the European Parliament and of the Council. *Official Journal of the European Union.* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=oj:JOL_2008_164_R_TOC

Faulkner, R. C., Farcas, A., & Merchant, N. D. (2018). Guiding principles for assessing the impact of underwater noise. *Journal of Applied Ecology*, *55*(6), 2531-2536. https://doi.org/10.1111/1365-2664.13161

Garthe, S., Schwemmer, H., Peschko, V., Markones, N., Müller, S., Schwemmer, P., & Mercker, M. (2023). Large-scale effects of offshore wind farms on seabirds of high conservation concern. *Scientific Reports*, *13*(1), 4779. https://doi.org/10.1038/s41598-023-31601-z

Geelhoed, S. C. V., Von Asmuth, R., Al Abbar, F., Leopold, M. F., Geert, &, & Aarts, M. (2017). Field testing the efficiency of the FaunaGuard Porpoise Module (FG-PM) in the Marsdiep area. *Wageningen University & Research.* Report C076/17

Gelcich, S., Buckley, P., Pinnegar, J. K., Chilvers, J., Lorenzoni, I., Terry, G., Guerrero, M., Castilla, J. C., Valdebenito, A., & Duarte, C. M. (2014). Public awareness, concerns, and priorities about anthropogenic impacts on marine environments. *Proceedings of the National Academy of Sciences*, *111*(42), 15042-15047. https://doi.org/10.1073/pnas.1417344111

Götz, T., & Janik, V. M. (2013). Acoustic deterrent devices to prevent pinniped depredation: Efficiency, conservation concerns and possible solutions. *Marine Ecology Progress Series*, *492*, 285-302. https://doi.org/10.3354/meps10482

Guenther, L., & Joubert, M. (2017). Science communication as a field of research: Identifying trends, challenges and gaps by analysing research papers. *Journal of Science Communication*, *16*(02), A02. https://doi.org/10.22323/2.16020202

Hamilton, P. M. (1957). Underwater hearing thresholds. *Journal of the Acoustical Society of America*, *29*, 792-794. https://doi.org/10.1121/1.1909056

Harding, S. & Cousins, N. (2022). Review of the Impacts of Anthropogenic Underwater Noise on Marine Biodiversity and Approaches to Manage and Mitigate them. *Technical Series No. 99. Secretariat of the Convention on Biological Diversity*, Montreal, 145 pages

Hawkins, A. D., Johnson, C., & Popper, A. N. (2020). How to set sound exposure criteria for fishes. *The Journal of the Acoustical Society of America*, *147*(3), 1762-1777. https://doi.org/10.1121/10.0000907

Hawkins, A. D., Pembroke, A. E., & Popper, A. N. (2015). Information gaps in understanding the effects of noise on fishes and invertebrates. *Reviews in Fish Biology and Fisheries*, *25*(1), 39-64. https://doi.org/10.1007/s11160-014-9369-3

Hawkins, A. D., & Popper, A. N. (2017). A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. *ICES Journal of Marine Science*, *74*(3), 635-651. https://doi.org/10.1093/icesjms/fsw205

Herbert-Read, J. E., Kremer, L., Bruintjes, R., Radford, A. N., & Ioannou, C. C. (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. https://doi.org/10.1098/rspb.2017.1627

Horst, M., Davies, S.R. & Irwin, A. (2016). Reframing science communication. In U. Felt, R. Fouché, C. A. Miller, & L. Smith-Doerr (Eds.), *The Handbook of Science and Technology Studies* (4 ed., pp. 881-908). MIT Press.

Hubert, J., & Neo, E. (2017). Testing spatial avoidance and behavioural changes in European seabass in a floating pen in response to sounds from the FaunaGuard-Fish Module (FG-FM).

Hubert, J., Neo, Y. Y., Winter, H. V., & Slabbekoorn, H. (2020). The role of ambient sound levels, signal-to-noise ratio, and stimulus pulse rate on behavioural disturbance of seabass in a net pen. *Behavioural Processes*, *170*, 103992. https://doi.org/10.1016/j.beproc.2019.103992

Hubert, J., Wille, D. A., & Slabbekoorn, H. (2020). Exploring effects of sound on the time budget of fishes: An experimental approach with captive cod. 010012. *Proceedings of Meetings on Acoustics.* https://doi.org/10.1121/2.0001253

Hutchison, Z., Secor, D., & Gill, A. (2020). The Interaction Between Resource Species and Electromagnetic Fields Associated with Electricity Production by Offshore Wind Farms. *Oceanography*, *33*(4), 96-107. https://doi.org/10.5670/oceanog.2020.409

Jakob-Hoff, R., Kingan, M., Fenemore, C., Schmid, G., Cockrem, J. F., Crackle, A., Van Bemmel, E., Connor, R., & Descovich, K. (2019). Potential Impact of Construction Noise on Selected Zoo Animals. *Animals*, *9*(8), 504. https://doi.org/10.3390/ani9080504

Karydis, M. (2011). Organizing a public aquarium: Objectives, design, operation and missions. A review. *Global NEST Journal*, *13*(4), 369-384. https://doi.org/10.30955/gnj.000702

Kleinberger, R. (2023). Sonic enrichment at the zoo: What will the zoo of the future sound like? *Interaction Studies. Social Behaviour and Communication in Biological and Artificial Systems*, *24*(2), 257-288. https://doi.org/10.1075/is.22044.kle

Kok, A. C. M., Bruil, L., Berges, B., Sakinan, S., Debusschere, E., Reubens, J., De Haan, D., Norro, A., & Slabbekoorn, H. (2021). An echosounder view on the potential effects of impulsive noise pollution on pelagic fish around wind farms in the North Sea. *Environmental Pollution*, *290*, 118063. https://doi.org/10.1016/j.envpol.2021.118063

Kratochvil, H., & Schwammer, H. (1997). Reducing acoustic disturbances by aquarium visitors. *Zoo Biology*, *16*(4), 349-353. https://doi.org/10.1002/(SICI)1098-2361(1997)16:4<349::AID-ZOO7>3.0.CO;2-A

Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., & Schmalenbach, I. (2017). Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment—Increased production rate of *Cancer pagurus*. *Marine Environmental Research*, *123*, 53-61. https://doi.org/10.1016/j.marenvres.2016.11.011

Lewis, R. N., Williams, L. J., De Kort, S. R., & Tucker Gilman, R. (2024). Assessing the effect of zoo closure on the soundscape using multiple acoustic indicators. *Ecological Indicators*, *158*, 111476. https://doi.org/10.1016/j.ecolind.2023.111476

Maes, J., Turnpenny, A. W. H., Lambert, D. R., Nedwell, J. R., Parmentier, A., & Ollevier, F. (2004). Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. *Journal of Fish Biology*, *64*(4), 938-946. https://doi.org/10.1111/j.1095-8649.2004.00360.x

Marmo, B., Roberts, I., Buckingham, M. P., King, S., & Booth, C. (2013). Modelling of Noise Effects of Operational Offshore Wind Turbines including noise transmission through various foundation types. Edinburgh: Scottish Government.

Massarsch, K. R., Fellenius, B. H., & Bodare, A. (2017). Fundamentals of the vibratory driving of piles and sheet piles. *Geotechnik*, *40*(2), 126-141. https://doi.org/10.1002/gete.201600018

Matuschek, R., & Betke, K. (2009). Measurements of Construction Noise During Pile Driving of Offshore Research Platforms and Wind Farms. *Institut für technische und angewandte Physik GmbH*

McConnell, B., Lonergan, M., & Dietz, R. (2012). *Interactions Between Seals and Offshore Wind Farms*.

Merchant, N. D., Putland, R. L., André, M., Baudin, E., Felli, M., Slabbekoorn, H., & Dekeling, R. (2022). A decade of underwater noise research in support of the European Marine Strategy Framework Directive. *Ocean & Coastal Management*, *228*, 106299. https://doi.org/10.1016/j.ocecoaman.2022.106299

Müller, A., & Zerbs, C. (2011). Measuring instruction for underwater sound monitoring. *Bundesamt für Seeschifffahrt und Hydrographie*.

Nedelec, S. L., Campbell, J., Radford, A. N., Simpson, S. D., & Merchant, N. D. (2016). Particle motion: The missing link in underwater acoustic ecology. *Methods in Ecology and Evolution*, *7*(7), 836-842. https://doi.org/10.1111/2041-210X.12544

Neo, Y. Y., Hubert, J., Bolle, L. J., Winter, H. V., & Slabbekoorn, H. (2018). European seabass respond more strongly to noise exposure at night and habituate over repeated trials of sound exposure. *Environmental Pollution*, *239*, 367-374. https://doi.org/10.1016/j.envpol.2018.04.018

NOAA (National Oceanic and Atmospheric Administration). (2024). What are pelagic fish? *National Ocean Service.* https://oceanservice.noaa.gov/facts/pelagic.html

Norro, A., Haelters, J., Rumes, B., & Degraer, S. (2010). Underwater noise produced by the piling activities during the construction of the Belwind offshore wind farm (Bligh Bank, Belgian marine waters).

Öhman, M. C., Sigray, P., & Westerberg, H. (2007). Offshore Windmills and the Effects of Electromagnetic Fields on Fish. *AMBIO: A Journal of the Human Environment*, *36*(8), 630-633. https://doi.org/10.1579/0044-7447(2007)36[630:OWATEO]2.0.CO;2

Orban, D. A., Soltis, J., Perkins, L., & Mellen, J. D. (2017). Sound at the zoo: Using animal monitoring, sound measurement, and noise reduction in zoo animal management. *Zoo Biology*, *36*(3), 231-236. https://doi.org/10.1002/zoo.21366

Parcerisas, C., Botteldooren, D., Devos, P., Hamard, Q., & Debusschere, E. (2024). Studying the Soundscape of Shallow and Heavy Used Marine Areas: Belgian Part of the North Sea. In *The Effects of Noise on Aquatic Life* (pp. 451-477). Springer, Cham. https://doi.org/10.1007/978-3-031-50256-9_122

Pelletier, C., Weladji, R. B., Lazure, L., & Paré, P. (2020). Zoo soundscape: Daily variation of low-to-high-frequency sounds. *Zoo Biology*, *39*(6), 374-381. https://doi.org/10.1002/zoo.21560

Pigeault, R., Ruser, A., Ramírez-Martínez, N. C., Geelhoed, S. C. V., Haelters, J., Nachtsheim, D. A., Schaffeld, T., Sveegaard, S., Siebert, U., & Gilles, A. (2024). Maritime traffic alters distribution of the harbour porpoise in the North Sea. *Marine Pollution Bulletin*, *208*, 116925. https://doi.org/10.1016/j.marpolbul.2024.116925

Popper, A. N., & Hawkins, A. D. (2018). The importance of particle motion to fishes and invertebrates. *The Journal of the Acoustical Society of America*, *143*(1), 470-488. https://doi.org/10.1121/1.5021594

Public Health Ontario (Ontario Agency for Health Protection and Promotion). (2023). Evidence brief: Risk Communication and Trust in Public Health during the COVID-19 Pandemic. Toronto, ON: King's Printer for Ontario

Putland, R. L., & Mensinger, A. F. (2019). Acoustic deterrents to manage fish populations. *Reviews in Fish Biology and Fisheries*, *29*(4), 789-807. https://doi.org/10.1007/s11160-019-09583-x

Quadros, S., Goulart, V. D. L., Passos, L., Vecci, M. A. M., & Young, R. J. (2014). Zoo visitor effect on mammal behaviour: Does noise matter? *Applied Animal Behaviour Science*, *156*, 78-84. https://doi.org/10.1016/j.applanim.2014.04.002

Rice, T., Badman-King, A., Hurn, S., Rose, P., & Reed, A. (2021). Listening after the animals: Sound and pastoral care in the zoo. *Journal of the Royal Anthropological Institute*, *27*(4), 850-869. https://doi.org/10.1111/1467-9655.13608

Rice, T., Reed, A., Badman-King, A., Hurn, S., & Rose, P. (2024). Listening to the Zoo: Challenging Zoo Visiting Conventions. *Ethnos*, *89*(1), 1-20. https://doi.org/10.1080/00141844.2021.1966070

Robinson, S. P., Theobald, P. D., & Lepper, P. A. (2013). Underwater noise generated from marine piling. *Proceedings of Meetings on Acoustics*. ECUA 2012 11th European Conference on Underwater Acoustics, Edinburgh, Scotland. https://doi.org/10.1121/1.4790330

Rumes, B., Erkman, A., & Haelters, J. (2013). EVALUATING UNDERWATER NOISE REGULATIONS FOR PILING NOISE IN BELGIUM AND THE NETHERLANDS.

Sand, O., Enger, P. S., Karlsen, H. E., Knudsen, F., & Kvernstuen, T. (2000). Avoidance responses of infrasound in downstream migrating European silver eels, Anguilla anguilla. *Environmental Biology of Fishes*, *57*(3), 327-336. https://doi.org/10.1023/A:1007575426155

Schuck, A., & Lange, G. (2007). Seismic methods. *Environmental Geology*.

Slabbekoorn, H. (2016). Aiming for Progress in Understanding Underwater Noise Impact on Fish: Complementary Need for Indoor and Outdoor Studies. In A. N. Popper & A. Hawkins (Red.), *The Effects of Noise on Aquatic Life II* (Vol. 875, pp. 1057-1065). Springer New York. https://doi.org/10.1007/978-1-4939-2981-8_131

Slabbekoorn, H., Bouton, N., Van Opzeeland, I., Coers, A., Ten Cate, C., & Popper, A. N. (2010). A noisy spring: The impact of globally rising underwater sound levels on fish. *Trends in Ecology & Evolution*, *25*(7), 419-427. https://doi.org/10.1016/j.tree.2010.04.005

Slabbekoorn, H., Dooling, R. J., Popper, A. N., & Fay, R. R. (Red.). (2018). *Effects of Anthropogenic Noise on Animals* (Vol. 66). Springer New York. https://doi.org/10.1007/978-1-4939-8574-6

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

Stenberg, C., Støttrup, J., Van Deurs, M., Berg, C., Dinesen, G., Mosegaard, H., Grome, T., & Leonhard, S. (2015). Long-term effects of an offshore wind farm in the North Sea on fish communities. *Marine Ecology Progress Series*, *528*, 257-265. https://doi.org/10.3354/meps11261

Strietman, W. J., Michels, R., & Leemans, E. (2018). Measures to reduce underwater noise and beach litter: An assessment of potential additional measures for the Netherlands. *Wageningen Economic Research.* https://doi.org/10.18174/457443

Svendsen, J. C., Ibanez-Erquiaga, B., Savina, E., & Wilms, T. (2022). Effects of operational off-shore wind farms on fishes and fisheries. Review report. In *Effects of operational off-shore wind farms on fishes and fisheries. Review report* [Report]. DTU Aqua.

Tennessen, J. B., Holt, M. M., Wright, B. M., Hanson, M. B., Emmons, C. K., Giles, D. A., Hogan, J. T., Thornton, S. J., & Deecke, V. B. (2024). Males miss and females forgo: Auditory masking from vessel noise impairs foraging efficiency and success in killer whales. *Global Change Biology*, *30*(9), e17490. https://doi.org/10.1111/gcb.17490

Ter Hofstede, R., Driessen, F. M. F., Elzinga, P. J., Van Koningsveld, M., & Schutter, M. (2022). Offshore wind farms contribute to epibenthic biodiversity in the North Sea. *Journal of Sea Research*, *185*, 102229. https://doi.org/10.1016/j.seares.2022.102229

Tsouvalas, A., & Metrikine, A. (2016). Structure-Borne Wave Radiation by Impact and Vibratory Piling in Offshore Installations: From Sound Prediction to Auditory Damage. *Journal of Marine Science and Engineering*, *4*(3), 44. https://doi.org/10.3390/jmse4030044

Van Der Knaap, I., Reubens, J., Thomas, L., Ainslie, M. A., Winter, H. V., Hubert, J., Martin, B., & Slabbekoorn, H. (2021). Effects of a seismic survey on movement of free-ranging Atlantic cod. *Current Biology*, *31*(7), 1555-1562.e4. https://doi.org/10.1016/j.cub.2021.01.050

Van Der Knaap, I., Slabbekoorn, H., Winter, H. V., Moens, T., & Reubens, J. (2021). Evaluating receiver contributions to acoustic positional telemetry: A case study on Atlantic cod around wind turbines in the North Sea. *Animal Biotelemetry*, *9*(1), 14. https://doi.org/10.1186/s40317-021-00238-y

Van Hal, R., Griffioen, A. B., & Van Keeken, O. A. (2017). Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm. *Marine Environmental Research*, *126*, 26-36. https://doi.org/10.1016/j.marenvres.2017.01.009

Veirs, S., Veirs, V., & Wood, J. D. (2016). Ship noise extends to frequencies used for echolocation by endangered killer whales. *PeerJ*, *4*, e1657. https://doi.org/10.7717/peerj.1657

Voss, J., Rose, A., Kosarev, V., Vilela, R., Van Opzeeland, I. C., & Diederichs, A. (2023). Response of harbor porpoises *(Phocoena phocoena)* to different types of acoustic harassment devices and subsequent piling during the construction of offshore wind farms. *Frontiers in Marine Science*, 1-14. https://doi.org/10.3389/fmars.2023.1128322

Williams, R., Wright, A. J., Ashe, E., Blight, L. K., Bruintjes, R., Canessa, R., Clark, C. W., Cullis-Suzuki, S., Dakin, D. T., Erbe, C., Hammond, P. S., Merchant, N. D., O'Hara, P. D., Purser, J., Radford, A. N., Simpson, S. D., Thomas, L., & Wale, M. A. (2015). Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. *Ocean & Coastal Management*, *115*, 17-24. https://doi.org/10.1016/j.ocecoaman.2015.05.021

WindEurope. (2025). Offshore Wind Ports Platform. https://windeurope.org/policy/topics/offshore-wind-ports/

Yoon, Y. G., Han, D.-G., & Choi, J. W. (2023). Measurements of underwater operational noise caused by offshore wind turbine off the southwest coast of Korea. *Frontiers in Marine Science*, *10*. https://doi.org/10.3389/fmars.2023.1153843