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

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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 7

General discussion

In the past decades, anthropogenic sound has become an increasingly prevalent pollutant to the environment, including underwater conditions (Hildebrand, 2009). With more and more offshore wind farms (OWFs) being built at sea (e.g. North Sea basin ambition stated in: European Commission, 2023), research into their effects on marine life has also increased. However, various aspects of the impact of OWFs on marine life are still poorly understood. In this thesis, I addressed some of the existing research gaps using both fundamental as well as applied studies. The focus species of the majority of this thesis were pelagic fish, a previously relatively understudied group with regards to potential impacts of OWFs. In the context of pile driving, I did a basin study to gain fundamental understanding of the behavioural response to acoustic deterrent sounds, by exposing wild-caught herring to various sound stimuli (chapters 2 and 3). This was then followed up by a more applied *in situ* study; exposing free-ranging pelagic fish to similar sound stimuli (chapter 4). For the operational phase of OWFs, pelagic fish, harbour porpoise and ambient noise levels were monitored in different wind parks along the Dutch-Belgian border in the North Sea (chapter 5). Finally, I did a science communication study focused on the human side of anthropogenic noise impact on fish, by testing different communication methods to reduce visitor noise in a public aquarium (chapter 6). Below, I summarise the main findings of each study and discuss potential opportunities for future research.

Improving sounds used for fish deterrent devices

One of the mitigation strategies for the detrimental effects of pile driving noise to nearby marine animals is the use of acoustic deterrent devices (ADDs) (Putland & Mensinger, 2019). These devices have been applied in different contexts and for various taxonomic groups (e.g. prevent pinniped depredation: Götz & Janik, 2013; redirect migrating fish: Sand et al., 2000) and can be used to direct animals away from a dangerous area in order to prevent future harm (e.g. redirect estuarine fish from a power plant cooling water inlet: Maes et al., 2004). However, in order for ADDs to be effective for pelagic fish at sea, fundamental understanding of how fish respond to certain sound stimuli is necessary. As discussed in chapters 2 and 3, I tested different sound stimuli on Atlantic herring (*Clupea harengus)* in a basin for their potential to evoke a behavioural response that could indicate suitability for use in ADDs. The sounds I tested in this study were developed based on a 'looming stimulus' hypothesis, as sounds with an increasing amplitude and accelerating pulse rate where expected to resemble a looming threat. Overall, the fish responded to the playback of the sound stimuli by an increase in turning rate, and their behavioural responsiveness did not decay over time during the study. However, I found no evidence that acoustic features of a 'looming' stimulus were more effective, as I found no significant variation among the different sound stimuli used. Although turning behaviour was observed in the basin study, in the follow-up study, testing similar sound stimuli with free-ranging pelagic fish at sea, no spatial avoidance was observed (chapter 4). The latter results suggest a lack of potential for the use of these types of sound stimuli for ADDs, at least for pelagic fish.

For the research aimed at improving current fish ADDs, I first did an indoor fundamental study with captive individuals, which was then followed up by an applied study in the field with free-ranging fish. In order to increase understanding of fish behaviour, captive studies allow for more control of environmental variables and for more detailed observations of the behaviour. These kinds of studies also typically allow for easier replication with animals of known background and homogenous samples with respect to age and experience. However, the interpretation of the results is often restricted to the captive settings since behavioural patterns in an unnatural setting are difficult to extrapolate to free-ranging individuals. Field studies, on the other hand, allow for direct *in situ* observation of the behaviour, but are often more challenging and expensive, especially at sea. Additionally, the high variability of the environment typically makes it more difficult to obtain larger sample sizes and detailed observations. Some researchers also opt for an in-between setup, such as a floating net pen which allows observation of captive individuals in a more natural environment, allowing natural light-dark cycles and tidal fluctuations (Hubert et al., 2020; Neo et al., 2016). A combination of both indoor and field studies, with captive and free-ranging fish, can therefore result in more significant progress in the research field of effects of anthropogenic noise on aquatic animal behaviour (Slabbekoorn, 2016).

Similarly, both fundamental and applied approaches to studies can be valuable to fill current research gaps. By definition, the main goal of fundamental research is to increase knowledge for the sake of knowledge. Unlike applied research, fundamental research has no immediate applied goal in mind. As these studies are typically exploratory, results may be unpredictable and unexpected, yet valuable (Courchamp et al., 2015). Often, fundamental studies provide insights that can form a basis or highlight the potential for new follow-up applied research. For example, knowledge on hearing ranges and response thresholds of various fish species is interesting to understand how they may hear and use sounds in their environment (fundamental). Results of these studies are in turn important to consider potential impacts of anthropogenic noise (applied). Similarly, to understand the impact of anthropogenic noise on an ecosystem, it is important to have prior fundamental knowledge of for example physical properties of the environment (e.g. currents) and interspecific relationships (e.g. predator-prey interactions). Interspecific dynamics may be affected by anthropogenic noise and play a role in the effect size of noise pollution impact on specific species (Francis & Barber, 2013; Kunc & Schmidt, 2021; Slabbekoorn et al., 2018). For example, boat noise exposure has been shown to decrease the anti-predator behaviour of sand gobies, which could have implications for their role in the food web (Kok et al., 2021). In another example, shore crabs (*Carcinus maenas*) aggregated less around a food item when exposed to broadband sound, which in turn released competitive pressure on common shrimps (*Crangon crangon*) (Hubert et al., 2018).

In this thesis, with the indoor study, we could test sound stimuli on multiple small groups of fish, allowing for detailed behavioural monitoring and replication. Fundamentally, I was interested to test if a 'looming' stimulus would elicit a similar response in fish as looming stimuli have been shown to do so in humans and some terrestrial mammal species, a hypothesis not previously tested. Ultimately, the applied goal for the overall project was to find sound stimuli that are suitable to use as ADDs. However, in the indoor study the fish could not really swim away from the speaker and were typically swimming near the edge of the round basin anyway. The fish responded to the sound stimuli by turning more, but the question remained if this would result in spatial avoidance of free-ranging individuals. The results of the follow-up applied study at sea suggested that the sound stimuli used are not effective to spatially deter pelagic fish. Since the turning response in the basin study did not translate to an avoidance response at sea (and they may have just turned more at sea as well), we could hypothesise that pelagic fish in the field do not show a spatial fleeing response as potential escape behaviour to a perceived risk or threat. They may just respond in a different way, for example by changing the schooling behaviour. In future studies, more alternative sound stimuli may be tested in their effectiveness to deter pelagic fish from future harmful areas (e.g. fishing boat sounds). However, it may also be fruitful to consider alternative mitigation measures to the potential harm of pile driving and other high-amplitude impulsive underwater noise (e.g. separating fish from and guiding away from sound sources by bubble curtains).

Pelagic fish and harbour porpoise in offshore wind farms

Since offshore wind farms (OWFs) typically have a lifespan of several decades, monitoring how marine life is affected by their operational stage is crucial to understand how the ecosystem is impacted, ultimately in order to be able to protect it. Marine animals are typically influenced by spatial and temporal variation in the environment and often have naturally occurring cycles of higher and lower abundance. The effects of increased variability in the environment by anthropogenic activities, such as OWFs, can be difficult to measure in situ. As described in chapter 5, we studied the impact of operational OWFs at the Dutch-Belgian border in the North Sea by conducting paired deployments. Using multi-sensor frames, we were able to measure variation in relative abundance of pelagic fish (with echosounders), vocal presence of harbour porpoise (*Phocoena phocoena)* (with C-PODS) and ambient noise levels (with hydrophones). In the paired setup of the study, four frames were deployed simultaneously: in repeated deployments, two were always placed in an operational OWF, and two near a shipwreck site as control non-OWF locations. In general, pelagic fish abundance and harbour porpoise presence were higher at night and towards autumn. In addition to these diurnal and seasonal fluctuations, the results revealed a lower fish abundance but higher harbour porpoise presence in the OWF locations. The ambient noise levels were lower at the OWF locations, an effect likely caused by increased distance from shipping lane traffic. Despite the distinct microhabitat-dependent variation between the two taxonomic groups, we also found a correlation in the data showing a significantly higher fish abundance if harbour porpoise were present.

As discussed more in detail in chapter 5, there are various possible explanations for the observed patterns of lower pelagic fish abundance and higher harbour porpoise presence in OWFs compared to control sites. Pelagic fish may find less food if turbines reduce primary production through increased vertical mixing (Cazenave et al., 2016; Floeter et al., 2017; van der Molen et al., 2014; van Duren et al., 2021; Wang et al., 2024), or may be deterred by a higher abundance of predators in OWF areas (Russell et al., 2014; results of current study). They may also be affected by the, although less intense, more unpredictable noise from for example maintenance ship activities. Harbour porpoise, on the other hand, may find more food around the turbines as a result of an artificial reef effect, and increased shelter due to the shipping restrictions in OWF areas. They may also prefer the lower ambient noise levels compared to the control sites (Kok et al., 2018). Although studies showing results such as ours provide key insights into effects of OWFs on important species groups, the explanations behind the patterns are mostly still speculative at this point. Future research should investigate the underlying causes behind these patterns more in depth. However, the effects from one wind farm may differ from another depending on its location, age, size, or even on the time when the study took place. Measuring these kinds of effects and inferring causal relationships in situ remains a challenge.

In order to monitor species of interest at sea, various methods can be used depending on the location and species. Fish can be locally caught to get an idea of their presence in the area. They can also be tagged in order to track their movements, as various types of tags can be used which are picked up by nearby sensors, a method also called 'telemetry' (Thorstad et al., 2014). Telemetry can also be applied to larger animals, by attaching acoustic tracking tags on their back (e.g. cetacean telemetry: Balmer et al., 2014). For larger species that are often near the water surface, such as aquatic mammals, visual surveys can be conducted from either a boat or an overflying airplane, yet this is usually limited to daylight and good-weather conditions. For various aquatic species, analysis of environmental DNA (eDNA) from water samples can also be useful for their identification and distribution (Rees et al., 2014). This way of monitoring is less invasive than traditional survey methods, as animals do not need to be disturbed. However, the method also has its limitations, since eDNA does not allow for real-time monitoring, and the spatial resolution and reliability depend on currents and turbulence (Rees et al., 2014). Recently, active (AAM) and passive acoustic monitoring (PAM) have gained applicability for monitoring various species in situ. With AAM, high-frequency sounds are emitted and animals are detected thanks to sensors picking up the reflected sound waves (e.g. echosounders for fish detection, note: emitted sounds are above the hearing range of most or all fishes). With PAM, sensors pick up the sounds produced by the species of interest (e.g. CPODs for harbour porpoise vocalisations). These acoustics methods allow for large scale monitoring at a fine temporal resolution (Ross et al., 2023), and are also not as invasive (and sometimes even with real-time observation possibility). Various sensors have been developed in the last decades, and have been improved over time, tailored to monitoring different species or animal groups.

In the monitoring study of APELAFICO, we acoustically tracked harbour porpoise (C-PODs) and pelagic fish (echosounders) simultaneously. The pairing of both monitoring methods can reveal interesting predator-prey relationships (Lawrence et al., 2016), as also indicated by the correlational data in our results. However, there is a possible unintended effect of this combination of methods to be considered, since the echosounder sounds are within the hearing range of harbour porpoise. Previous research has already indicated that various forms of sonar can affect some cetacean species. For example, the exposure to naval sonar can change the diving behaviour of killer whales *(Orcinus orca*), long-filled pilot whales (*Globicephala melas*) and sperm whales (*Physeter macrocephalus*) (Sivle et al., 2012). On the other hand, echosounders are sometimes also used to detect marine mammals. For example, bottom-mounted echosounder have been proven useful to monitor cetaceans (Doksæter et al., 2009). In a recent extended analysis of our integrated data, the results indeed suggest that harbour porpoise may be deterred or at least become vocally less active during and/or right after the use of echosounders (Hubert et al., unpublished). This finding warrants future research and should be taken into account when similar studies want to monitor both cetaceans and their prey at the same time.

Reducing visitor noise at a public aquarium

In my final year of the four-year PhD-project, I focused on the human side of effects of elevated ambient noise on fish. It is important to increase the attention towards the effects of noise pollution on (aquatic) animals. In many places, animals and people are in close proximity to each other and often influence each other's behaviour. Examples of those places are natural parks, reserves, zoos and public aquaria. Here, visitors are one of the main sources of elevated ambient noise levels that animals are regularly exposed to. Recently, although there is increased awareness about effects of noisy conditions on animals in zoo and aquarium exhibits recently, the mitigation methods are not always effective or empirically tested.

As described in chapter 6, I used different variants of a newly designed information sign to test which one was most effective to reduce visitor noise at the Blijdorp Zoo in Rotterdam (the Netherlands). I additionally tested the effectiveness of adding a voice message on top of using a sign. In this study, I measured both the ambient noise levels near the aquarium walls and took visitor surveys. Both types of data showed that using signs indeed made visitors more quiet. However, the phrasing on the signs did not seem to matter, as all types had a similar effect. Since one of the signs also provided an explanation as to why reducing noise is favourable (stating that fish can also hear and be affected by noise), this sign is now selected to be used at the zoo to reduce visitor noise and educate visitors at the same time. The data from the surveys also allowed me to get an idea about how visitors think about their contribution and exposure to noise at the aquarium. The results of the study further showed that, although the addition of a voice message did make the text sign stand out more, it did not reduce the visitor noise more.

The reason for setting up this study in the Oceanium of the Blijdorp Zoo was two-fold: (1) Considering the main topic of this thesis is effects of human-made noise on fish behaviour, I first had the welfare of the fish and other animals in the exhibits in mind. It can get quite loud in places like zoos and public aquaria, not just sounds from visitors but also from construction periods and the pump and filter systems. Previous studies on how animals in exhibits may be affected by noisy conditions have reported altered behaviour in Atlantic cod (*Gadus morhua*) and saithe (*Pollachius virens*) (Andersson et al., 2023), increased plasma cortisol concentrations and increased parasites affecting kidneys, and increased behavioural variability in lined seahorses *(Hippocampus erectus)*, of which the latter effect seemed to diminish after a week (Anderson et al., 2011). Although the effects of visitor noise on behaviour or physiology were not tested in this study at the Oceanium of the Rotterdam Zoo, reducing visitor noise will also here likely be beneficial to the welfare of the animals in the large aquarium.

(2) Since the fourth year of my PhD allowed for a different approach, this time the focus was on science communication and society. Therefore, I wanted to gain insight into the experience of the visitors themselves regarding the noisy environment at the aquarium. Most likely in those locations where anthropogenic noise impacts nearby animals, there is also an effect on nearby people. For example, traffic noise in busy cities has been shown to impact various animals, such as birds (e.g. vocal adjustment by great tits: Halfwerk et al., 2012; spatial avoidance by zebra finches: Liu et al., 2020), while also for humans, traffic noise has been shown to come with a list of health hazards already (Singh et al., 2018). A relatively recent study investigated if experimentally reducing traffic noise is beneficial to both bird habitat quality and visitor experience in a natural park (Levenhagen et al., 2021). This study was only able to reveal a positive impact for the visitors and not an effect on the birds, which may have been too subtle or would only become apparent after a longer period. A similar thing may be true for zoos or public aquaria, viewing the reduction of anthropogenic noise as multipurpose: for animals as well as visitors.

Even though the abilities of auditory perception of fishes and humans are quite different, they can both be affected by noisy environments (Basner, 2015; Popper & Hawkins, 2018; Slabbekoorn et al., 2010). In chapter one of this thesis, we therefore also considered the hypothesis that a looming stimulus, that affects humans and some other terrestrial mammals, could also scare fish. Although the results showed that the looming stimulus features did not evoke a stronger response than the other stimuli, it is still worthwhile to test such hypotheses. This is especially true in environments where humans and animals meet and sometimes closely interact, such as in cities or zoos. As humans and animals may both benefit from noise reduction measurements, a future approach could be more holistic, indeed taking more potentially affected taxonomic groups into account. Such a holistic mindset is already the case when talking about the so-called ‘One Health’ principle.

The One Health High-Level Expert Panel (OHHLEP) defines One Health as “an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent” (OHHLEP et al., 2022, p. 2). This principle has gained more attention since the recent Covid-pandemic, as it demonstrates the close connection between society, animals and their shared environment. The OHHLEP describes the focus of the approach to include the need for healthy water, food, energy and air, and to take action for climate change and sustainable development. I would argue we can take this approach even further and add the reduction of anthropogenic noise pollution to the list of focus points. Future research could take an interdisciplinary approach and a broader look at noise pollution for key animal species, as well as humans at the same time. Specific studies could test how much overlap there is between what kind of sounds affect some animal species and humans, and how best to manage it for the benefit of both groups.

Conclusions

In the various studies of this thesis we considered certain sounds as either a meaningful *message* or a superfluous and potentially annoying *noise*. (1) *Sound as a message*: there is information contained in a sound, a signal which can be of interest for animals and humans. In chapters 2, 3 and 4 we tried to improve sound stimuli to use in acoustic deterrent devices. In this context, the message in the sound stimuli can be summarised as *'it is unsafe here'*, as we hoped pelagic fish would flee the area before the detrimentally high-amplitude impulsive sounds from pile driving for offshore wind farms will take place. Results of these studies indicated that although fish may receive this message, they may not flee as a response. In chapter 6, we played an audio message at the entrance of the Oceanium at Blijdorp Zoo. The sound in this case contained a message in asking visitors to be quieter. However, the results showed using a message on a sign was already effective, and there was no stronger effect of adding the audio message on top of signage. (2) *Sound as a noise*: if a sound is unwanted, unpleasant or disruptive. The underwater world is inherently noisy and anthropogenic noise in particular is very present and still increasing (Duarte et al., 2021). In many places, humans and animals are near each other and human activities can impact animal behaviour and welfare. In the North Sea, among other coastal areas, there's an increasing amount of offshore wind farms (OWFs) (European Commission, 2023), changing more and more of the environment. We found more harbour porpoise presence but less pelagic fish abundance in the OWF sites, compared to the shipwreck control sites. Noticeably, the average ambient noise levels were higher at the control sites, potentially caused by proximity to busy shipping lanes. The sound from Oceanium visitors at Blijdorp Zoo could also be considered a potentially disruptive noise to both animals in the aquatic exhibits and fellow visitors. The study showed that more than a third of visitors reported being bothered by noise in the shark tunnel, and lowering the sounds from visitors was possible using signs. To summarise, animals and humans are constantly exposed to various sounds, perceived as meaningful messages or superfluous noises and which they may or may not care about, but that deserve our attention and awareness in the context of potential welfare and appraisal issues.

Anthropogenic noise pollution is of course only one of multiple stressors that animals (and humans) currently face. Although research focusing specifically on an effect of noise pollution on species and communities yields valuable insights, in reality in nature this stressor is rarely ever present in isolation. In marine systems, various studies investigating at least two stressors indicate the cumulative effects of stressors can be additive, synergistic or antagonistic (meta-analysis: Crain et al., 2008; also see Piggott et al., 2015). For example, the increase in OWFs comes with many different changes to the environment besides ambient noise levels, such as changes in bottom structure, water currents and layer mixing (Carpenter et al., 2016), electro-magnetic fields (Hutchison et al., 2020), artificial reef effects (Degraer et al., 2020), and more. Simultaneously, current changes at a global scale include rising average water temperatures and ocean acidity (Godbold & Calosi, 2013), as well as higher fishing intensity, increasingly complicating the environment to which animals must adapt. Consequently, a shift towards more renewable energy by implementing more OWFs is of course desirable, in order to slow-down global warming.

In any case, it is important to always take sound into account when addressing marine ecological impact from anthropogenic activities at sea. This does not reduce the relevance or the need of considering the 'bigger picture' of accumulating stressors of all kinds. As mentioned before, for some species, operational OWFs can be beneficial, while for others survival or reproductive opportunities may be reduced. As many different ecological aspects change with the expanding range of OWF areas, it remains a challenge to estimate if the 'net' outcome is or will be positive, negative or somewhere in between. However, in the multitude of changes to the environment, anthropogenic noise pollution has only received more attention relatively recently (Duarte et al., 2021; Slabbekoorn et al., 2010). Considering the global scale of this pollutant, it should also receive substantial attention in future studies and policies. Just as other global change consequences can be addressed holistically for the sake of both human and animal welfare, anthropogenic noise pollution should be integrated in a broader approach to ecosystem management and conservation.

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