Agenda Item 3.5 | Implementation Review: Research

Investigation of the Effects of Anthropogenic Sounds on Harbour Porpoises (Action 11)

Information Document 3.5a | Effect Ranges of Underwater Noise from Anchor Vibration Operations in the Wadden Sea

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Effect ranges of underwater noise from anchor vibration operations in the Wadden Sea

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ABSTRACT

Anchor pipe vibration embedment operations during the construction of seed mussel collectors were performed in the Wadden Sea, a designated World Heritage Site by UNESCO in 2009. We recorded 200 min of underwater noise during the construction of seven anchor pipes. Underwater noise was recorded simultaneously at three positions with a water depth of 9 m with increasing distance to the construction site to assess the disturbance potential to the marine fauna. The recorded vibration embedment noise was a continuous sound with durations of 2–55 s, with most energy below 1 kHz and peak frequencies around 900 Hz. Background noise level at a distance of approximately 1 km increased around 13 dB at frequencies between 800 and 1000 Hz. We estimated the sound propagation by a non-linear logarithmic regression by means of the intercept, slope and attenuation factor, which allowed us to evaluate the received sound levels that reach an animal in certain distances from the construction site. The estimated sound exposure level (SEL) of the source was 148.2 dB re 1 $\mu Pa^2 s$ and the median SEL ranged from 120 to 99 dB re 1 $\mu Pa^2 s$ at distances between 394 and 2288 m, respectively. Behavioural thresholds for indigenous species of marine mammals in the Wadden Sea as well as representative fish species were used to determine effect radii of vibration embedment noise. Our study showed that the detected anchor pipe vibration embedment noise might exert a behavioural reaction on a local scale. Marine mammals could be affected by the construction operations up to a distance of 375 m and fish up to a distance of 766 m. These zones of responsiveness for vibration embedment operations are relatively small, compared to pile driving, which is regularly used during construction operations. Our study shows that it is important to monitor and assess any kind of noise introduction to verify, whether a sustainable human use with respect to the complied guidelines is ensured without affecting the marine fauna. That is the first step to maintain a good environmental status as implemented in the MSFD.

1. Introduction

The Wadden Sea is one of the largest intertidal areas in the world, with extensive wetland areas characterised by large intertidal flats stretching from the Netherlands to Denmark (Hild, 1999). Indigenous marine mammal species in the Wadden Sea are the common seal (*Phoca vitulina*), the grey seal (*Halichoerus grypus*) and the harbour porpoise (*Phocoena phocoena*) (Jensen et al., 2017). The Dutch and German parts of the Wadden Sea Conservation Area have been designated as a World Heritage Site by UNESCO in June 2009, recognising the global importance of the Wadden Sea as a nature area (CWSS, 2017). The Wadden Sea region is an area where people work, but also come for leisure or recreational activities. About 3.7 million people live along the Wadden Sea coast interacting with the landscape, plants and wildlife. The Trilateral Wadden Sea Plan (2010) concedes that sustainable human use has to be continuously balanced in a harmonious relationship between the needs of society and ecological integrity (CWSS, 2010).

Activities at sea increased extensively over the last decades, among which shipping, fisheries, tourism, military activities, dredging and energy exploitation are the most concerning activities (CWSS, 2017). These activities contribute a lot to ambient underwater noise (Rako-

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Gospić and Picciulin, 2019). The introduction of noise into the oceans is getting more and more in focus when it comes to impact assessment of anthropogenic activities on the environment.

The North- and Baltic Seas are classified as two areas with excessive human exploitation (Halpern et al., 2015). In offshore areas of the North Sea many wind farms have already been constructed and a lot more are planned, which is accompanied by the introduction of impulsive noise of high energy. In comparison, in shallow coastal waters noise is a chronic and constant pollution due to urbanisation, shipping and expanding tourism. Along with those activities, studies have been conducted to figure out, to which extent marine life is affected by underwater noise and how severe potential effects might be.

Anthropogenic noise can cause behavioural responses of harbour porpoises (Kastelein et al., 2013b, 2013c) or lead to changes in spatial distribution (Brandt et al., 2016; Carstensen et al., 2006; Dähne et al., 2013; Scheidat et al., 2011; Teilmann and Carstensen, 2012; Tougaard et al., 2009). Even hearing impairment resulting in a temporary threshold shift (TTS) has been documented by Lucke et al. (2009) or Kastelein et al. (2016) after the exposure to impulsive noise, such as pile driving strikes. Other responses of porpoises can be stress or the interruption of their natural behaviour, such as feeding (Wisniewska et al., 2018). Behavioural responses towards pile driving of a Dutch wind farm were documented for both, harbour (Heinis, 2013) and grey seals (Aarts et al., 2018). Russell et al. (2016) predicted a displacement of harbour seals in response to pile driving.

There are also studies of anthropogenic noise affecting different fish species by deteriorating body condition (Bruintjes et al., 2016; Buscaino et al., 2010; Casper et al., 2013a, 2013b), decreasing catch rates (Purser and Radford, 2011), inhibiting anti-predator defence (Simpson et al., 2016; Spiga et al., 2017; Voellmy et al., 2014) or changing school coordination (Hawkins et al., 2014; Herbert-Read et al., 2017) and cohesion (Kastelein et al., 2017; Neo et al., 2014). Reproduction of fish could also be affected, if anthropogenic noise causes masking and therefore disrupts the intra-specific communication. This masking can result in an increase in amplitude of communication signals to compensate for a decreased signal-to-noise ratio, also known as the Lombard effect (Holt and Johnston, 2014; Ladich, 2019; Luczkovich et al., 2016).

To assess and quantify environmental effects of anthropogenic noise, it is crucial to estimate the levels of sound generated by the sender (source level) and the rate at which the sound decays as it propagates to the receiver (transmission loss) (Rako-Gospić and Picciulin, 2019). All those studies show that underwater noise has a huge effect on the marine environment and is therefore of international concern. Thus, it is important to monitor and assess the introduction of noise. This is crucial to develop measures to keep the noise levels low in order to achieve a good environmental status (GES) as implemented in the marine strategy framework directive (MSFD, Descriptor 11, European Union, 2008).

In addition to the three occurring marine mammal species, the shallow Wadden Sea is an important area for many fish species, which rely on the coastal area for at least one part of their life cycles (Tulp et al., 2017). Numerous species of marine fish (flatfish, other benthic and pelagic fish species) reach the Wadden Sea as post-larvae and spend their juvenile phase there benefitting from the high food availability and shelter from predators (marine juveniles e.g. plaice (*Pleuronectes platessa*), sole (*Solea solea*), dab (*Limanda limanda*), whiting (*Merlangus merlangus*), cod (*Gadus morhua*), sea bass (*Dicentrarchus labrax*) and herring (*Clupea harengus*) (Elliott et al., 2007; Van der Veer et al., 2000). Other species cross the region on their way to either marine or fresh water spawning sites. These species can be diadromous, such as eel (*Anguilla anguilla*), or anadromous like smelt (*Osmerus eperlanus*), twaite shad (*Alosa fallax*), river lamprey (*Lampetra fluviatilis*) and sea lamprey (*Petromyzon marinus*). Others visit the area during certain times of the year like marine seasonal migrants, such as anchovy (*Engraulis encrasicolus*) and pilchard (*Sardina pilchardus*)) or only sporadically like marine adventitious species, such as mullets (Mugilidae) and sprat (*Sprattus sprattus*) (Elliott et al., 2007). Apart from the temporary visitors, the Wadden Sea is also inhabited by resident species that spend (almost) their entire life in the Wadden Sea (e.g. flounder (*Platichthys flesus*), eelpout (*Zoacres viviparous*), bullrout (*Myoxocephalus scorpius*), fivebeard rockling (*Ciliata mustela*), hooknose (*Agonus cataphractus*) and pipefishes (*Syngnathus sp.*)) (Tulp et al., 2017).

The Wadden Sea represents a rich food source for humans, offering large amounts of natural grown mussel beds. Nowadays, it is more profitable to rather cultivate mussels in the Wadden Sea than harvesting from natural sites. This is practised with blue mussel (*Mytilus edulis*) cultures by placing wild-caught mussel seeds (spat) at specific sites, i.e. on-bottom culture plots, where survival and growth is enhanced. As an alternative to catching the spat, artificial seed collection technologies, such as seed mussel collectors (SMCs) are used. SMCs are fixed or hanging net constructions where mussel larvae can settle on and develop into young mussels that will be harvested. Therefore, anchor pipes are fixed to the ground, either through pile driving or drilling, which is accompanied by the introduction of high noise levels into the water (Brandt et al., 2018). An alternative form of SMC construction is to vibrate anchor pipes into the seabed.

The aim of this study was to assess the effects of underwater noise from the construction of seed mussel collectors on the marine mammals and fish in the Wadden Sea. Therefore, we conducted empirical noise measurements during the construction of seven anchor pipes. We aimed to determine accurate estimates of received levels at a range of distances from the source with a propagation model and evaluate the potential impacts on marine fauna based on sound exposure level thresholds from the literature for marine mammals and fish.

2. Material and methods

2.1. Study area and anchor pipes vibration embedment operations

Fieldwork was conducted in the German Wadden Sea in the tidal creek ‘Sueder Piep’ off the coast of Schleswig-Holstein (North Sea) at 25th of April in 2019 (Fig. 1). Underwater recordings during the construction of seven anchor pipes were conducted during 200 min simultaneously at three measuring positions in order to determine underwater noise attenuation by distance. Therefore, three recording buoys consisting of a PVC rod, a floating body and an 18 mm nylon rope were placed at distances between 400 and 2300 m from the construction site. Additionally, a small anchor stone was attached to the system to keep the buoy in position. On each buoy we fixed a SoundTrap (ST300 HF, Ocean Instruments ^{NZ}, Acoustic Monitoring Systems), a compact self-contained underwater sound recorder for ocean acoustic research. The water depth at the measuring positions was 9 m and all SoundTraps were deployed at a depth of 4.5 m. The devices were linked to GPS (Global Positioning System)-receivers placed at the PVC rod of the buoy via a cable to associate acoustic recordings (wave-files) to the specific position of the buoy and to synchronise recordings and distance to the construction activities. A sample rate of 576 kHz was used to record the vibration sounds.

2.2. Sound propagation modelling and frequency analysis

Underwater recordings were analysed to determine the sound propagation in the construction area. The calculated sound propagation is essential to determine sound exposure levels (SEL) within the acoustic field of all anchor pipe vibration embedment events the surrounding marine fauna might be exposed to. To calculate the SEL, underwater recordings were loaded with the R package ‘tuneR’ (Ligges et al., 2016) and high pass filtered (Butterworth) with a 1st order filter to 100 Hz, to eliminate a possible offset with the R package ‘seewave’ (Sueur et al., 2008). Anchor pipe vibration embedment in the recordings was detected by visually screening the spectrograms (Fast Fourier Transform: 16384, Hanning window, 50% overlap) and listening to the underwater recordings in Adobe Audition 3.0. The SEL was calculated according to

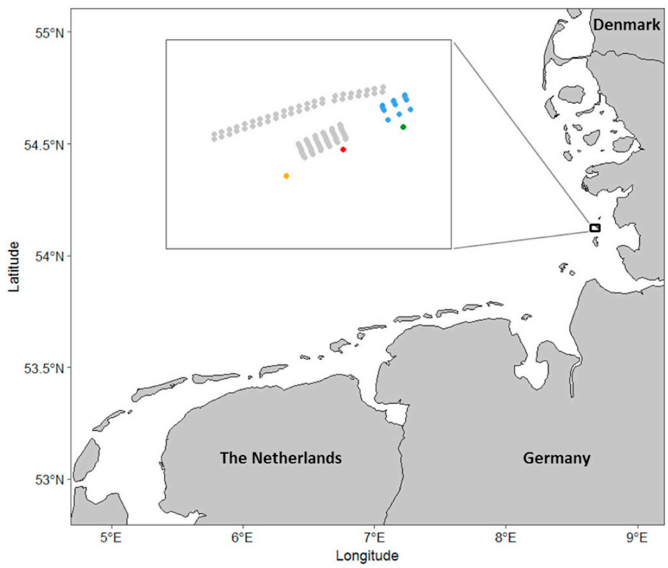

Fig. 1. Map of the North Sea coastline including the entire Wadden Sea area with an enlarged section of the area of investigation (square therein). Recording buoys were bottom mounted at three measuring positions (red, green and yellow dots) around the construction site (blue dots) for culturing areas for seed mussels at distances between 400 and 2300 m to anchor pipe vibration embedment sites. The water depth at the measuring positions was 9 m and all recorders were deployed at a depth of 4.5 m. Grey dots show positions of additional piles without available underwater noise recordings, because they were already vibrated into the seabed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the ISO 1996-1:2016 (International Organization for Standardization, 2016) as:

$$SEL = 10 \times \log_{10} \frac{E}{E_0},$$

where $E = \int_0^T p(t)^2 dt$, for a 1 s time window.

The sound propagation was based on the median SEL_{50} and the SEL_{05}, defined as the noise levels exceeded by 50% and 5% of all values, respectively. The sound propagation in relation to the distances to the anchor pipe vibration embedment site was estimated by a non-linear regression. The intercept and the logarithmic regression factor were estimated by a non-linear least squares (nls) approach, using the nls function in R (R Core Team, 2017). We further estimated an attenuation factor A accounting for absorption and further complicating factors, such as multipath propagation, refraction, diffraction and scattering of sound due to suspended particles in the water column (Urick, 1983) within the nls approach.

Background noise was determined for a 30 s fraction of underwater sound recordings prior to construction activities. Third octave spectra were calculated for centre frequencies ranging from 62.5 Hz to 128 kHz for each 100 Hz high pass filtered 1 s window within the fraction, for each anchor pipe at each measuring position. In total, background noise recordings prior to seven anchor pipe vibration events at three measuring positions were analysed, building a data base of eleven 30 s windows.

All analyses were performed and figures created using R (R Core Team, 2017).

3. Results

3.1. Sound propagation in the study area

Underwater recordings during the construction of seven anchor pipes were conducted during 200 min in order to determine underwater

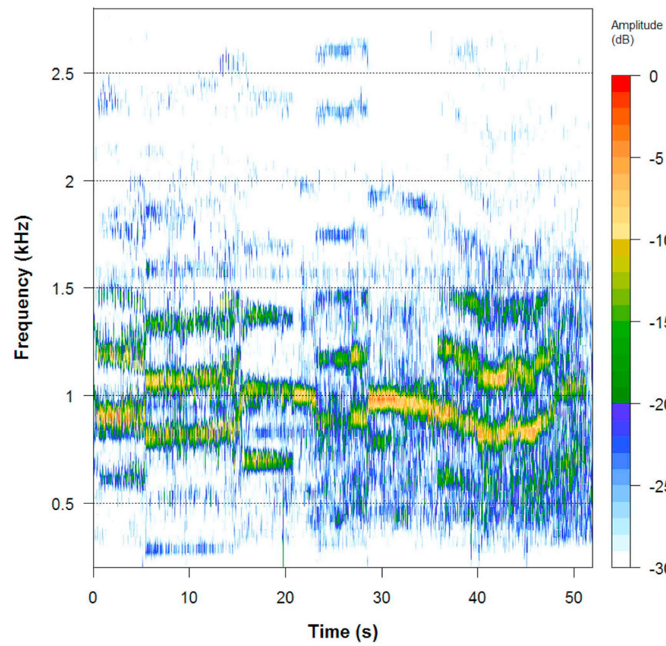

Fig. 2. Spectrogram of the first detected anchor pipe vibration embedment noise with a duration of 52 s recorded at around 1 km distance to the pile. Fast Fourier Transform: 16384, Hanning window, 50% overlap. The dB scale is colour-coded with red as the highest and blue the lowest intensity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

noise. The detected vibration embedment noise can be defined as continuous sound with durations from 2 to 55 s. Energy spectra show that most of the energy was found below 1 kHz with a peak around 900 Hz (see Fig. 2).

Fig. 3 shows the median third octave sound exposure level (SEL in dB re 1 $\mu Pa^2 s$) of the vibration embedment noise (red) at a distance of approximately 1 km seen in the spectrogram (Fig. 2) in relation to background noise (green). In the frequency range from 630 Hz to 25 kHz the noise generated by anchor pipe vibration embedment operations exceeded the background noise level, particularly at 800–1000 Hz by around 13 dB (Fig. 3).

The sound propagation was estimated by a non-linear logarithmic regression, estimating the intercept, slope and attenuation factor based on the determined SEL per second. The best fit was determined at:

Received level: $148.2 - 10.05 \times log_{10}(R) + 0.0067(R)$, where R accounts for the distance.

Thus, the estimated source level resulting from the intercept was 148.2 dB re 1 $\mu Pa^2 s$.

The transmission loss is shown in Fig. 4.

The received median SEL_{50} ranged from 120 to 99 dB re 1 $\mu Pa^2 s$ and the received median SEL_{05} ranged from 125 to 103 dB re 1 $\mu Pa^2 s$ at distances between 394 and 2288 m, respectively (Fig. 4).

4. Discussion

Our recordings quantified the introduced underwater noise into the Wadden Sea marine environment by the construction of seed mussel collectors. The background noise was already slightly elevated due to the presence of three ships involved with construction activities (such as vibration embedment, painting and construction supervision) or passing ships due to the construction site being close to a fairway. The source level of anchor pipe vibration embedment operations was determined at 148.2 dB re 1 $\mu Pa^2 s$ and can be considered as relatively low compared to pile driving of small diameter (0.61 or 0.71 m) piles with a source SEL of 192 dB re 1 $\mu Pa^2 s$ at 1 m investigated by Leunissen and

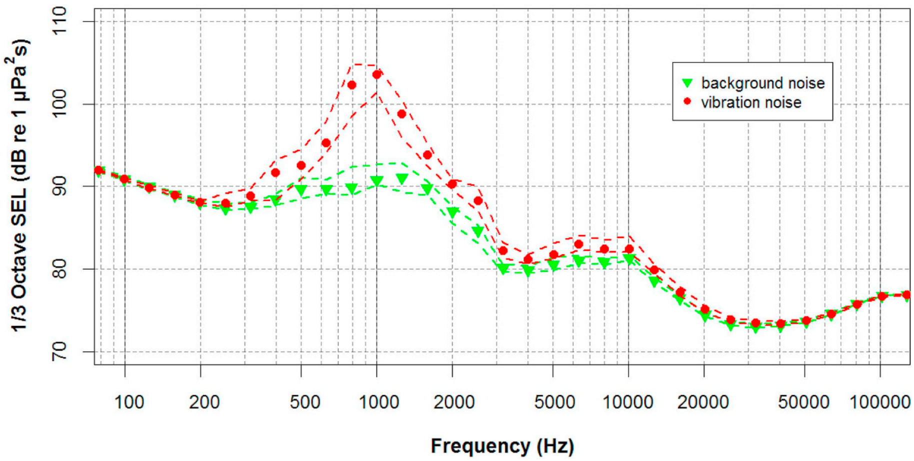

Fig. 3. Median third octave sound exposure level (SEL) for the first detected anchor pipe vibration embedment noise event (red dots) relative to the background noise (green triangles), measured at a distance of about 1 km. The dashed lines display the 0.25 (lower) and 0.75 (upper) quantiles for vibration and background noise, respectively. The SEL of the vibration noise was calculated for each third octave and each second in a 52 s time window according to Fig. 2. The background noise SEL was calculated the same way for the same time window (52 s) right before the construction work began. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

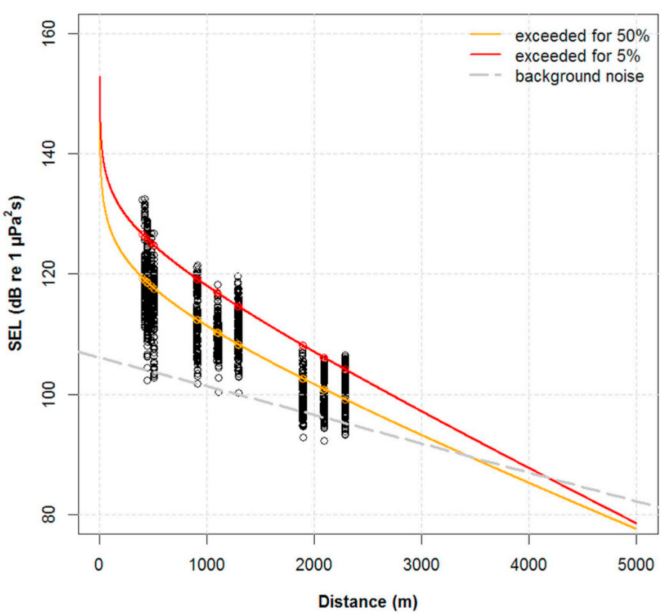

Fig. 4. Calculated transmission loss for the median sound exposure level (SEL_{50}, orange line) and the sound exposure level exceeded for 5% (SEL_{05}, red line) of all detected vibration embedment noise events (black circles), respectively as well as for the background noise (grey dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Dawson (2018). Nevertheless, the signal exceeds background noise levels out to around 3000 m from the construction site and is therefore audible for the marine fauna. The construction for each anchor pile took 2 and 55 s and was interrupted by multiple breaks, most likely to readjust the anchor pile and vibration embedment equipment. The vibration embedment operations produced continuous noise, which was also stated by Branstetter et al. (2018) for vibratory pile driving. The vibration noise contained most of the energy below 1 kHz and did not contain distinct high-energy incidents in the construction periods.

Based on the calculated transmission loss, we were able to evaluate the received sound levels that reach an animal at a certain distance from the construction site. In terms of frequency content, the noise generated by anchor pipe vibration embedment operations was comparable to impulsive noise sources like airguns (Lucke et al., 2009) or pile driving noise (Dähne et al., 2017). These impulsive noise events lose their characteristics, when recorded at larger distances. The repetition of these impulsive noise events may become diffuse with distance and reverberation and become indistinguishable from continuous noise (van der Graaf et al., 2012).

4.1. Potential effect on marine mammals

Noise exposure can induce hearing shifts, which can occur permanently or temporarily. In comparison to the estimated source levels of the construction work in this study, much higher source levels are needed to induce hearing impairment (Lucke et al., 2009). Our focus is on behavioural reaction thresholds that occur at larger distances from the source where received levels are lower compared to those causing a TTS. Thus, we can proceed from this assumption. Vessel noise, as a continuous noise source, contains also most of the energy below 1 kHz, but can be very variable, depending on vessel type, propeller and speed (Kipple and Gabriele, 2004; Kipple and Gabriele, 2003; Putland et al., 2017) and includes also high frequency content to which animals might respond (Dyndo et al., 2015). Therefore, our impact assessment of the recorded vibration embedment noise was based on thresholds derived from studies on impulsive noise (Aarts et al., 2018; Kastelein et al., 2016; Lucke et al., 2009). Thresholds for behavioural reactions could be found in the literature for indigenous species of marine mammals in the Wadden Sea (harbour porpoise, harbour seal and grey seal) as well as representative fish species (herring, sole, cod). Based on the data from the literature and the calculated transmission loss we were able to determine effect radii for marine mammals inhabiting the German Wadden Sea (Fig. 5). The figure displays effect radii based on the transmission loss for the median SEL_{50} (dashed line) and the SEL_{05} (solid line), defined as the noise levels exceeded by 50% and 5% of all detected vibration embedment noise events, respectively. Due to the relatively low determined source level of 148.2 dB re 1 µPa^{2}s a TTS from the vibration embedment noise is unlikely. Although it could be shown for harbour porpoises, that multiple exposure to pile driving strikes with single sound exposure levels of 145 dB re 1 µPa^{2}s has the potential to induce a TTS, if a cumulative energy of 175 dB re 1 µPa^{2}s is reached (Kastelein et al., 2016). However, the short duration of construction work and the breaks in between are unlikely to induce hearing shifts, even for multiple exposure.

Behavioural reactions might be induced more likely . Thus, Lucke et al. (2009) found that a single harbour porpoise consistently showed aversive behavioural reactions to pulsed sound from an airgun at a received SEL of 145 dB re 1 µPa^{2}s. This is the same threshold at which evasive actions had been predicted for harbour seals (Heinis, 2013), based on the hearing ability and response of captive animals (Kastelein et al., 2013a). Our determined SEL is also well in the range of the findings of Russell et al. (2016). They predicted a displacement of harbour seals as a response to pile driving at SELs between 142 and 151 dB re 1 µPa^{2}s. A SEL of 145 dB re 1 µPa^{2}s can be reached at a distance of 2 m (up to 8 m for the SEL_{05}) from the construction site,

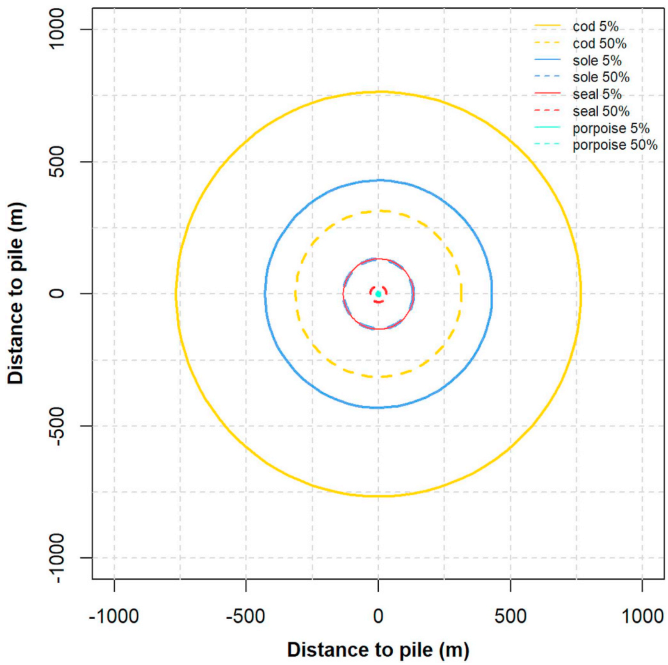

Fig. 5. Effect radii to the vibration embedment location for different fish and marine mammal species living in the German Wadden Sea: Cod (yellow), sole (blue), seal (red) and harbour porpoise (turquoise). The effect radii are calculated for the sound exposure level (SEL) of the vibration noise exceeded for 5% and for 50%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resulting from the estimated intercept, slope and attenuation factor given by the non-linear logarithmic regression.

A study on grey seals indicated that a behavioural response to pile driving occurred in response to a SEL of 133 dB re 1 μPa^{2}s. At this threshold a change in descent speed could be observed. Moreover, exceeding a SEL of ~137 dB re 1 μPa^{2}s leads to a significant behavioural response in any of the dive or movement variables (Aarts et al., 2018). This threshold could be reached around 31 m (up to 132 m for the SEL_{05}) from the SMC construction site.

Harbour porpoises react to underwater noise in the most sensitive way. The lowest threshold has been found by Kastelein et al. (2013c), who showed that above a received broadband sound exposure level of 127 dB re 1 μPa^{2}s the respiration rate of harbour porpoises increased in response to the pile driving sounds. This would correspond to a received SEL at a distance of 109 m (up to 375 m for the SEL_{05}) from the construction site.

Estimated zones of responsiveness for marine mammals differ between harbour seals, grey seals and harbour porpoises for anchor pipe vibration embedment operations. This might be related to the sensitiveness of the measurement of the reaction (respiration rate vs. aversive behaviour or change in dive speed) or variability in the response of animals in the wild and in human care. The expected hazard zones, extending from 2 to 375 m from the anchor pipe vibration embedment operations can be considered as negligible for the indigenous species of marine mammals in the Wadden Sea (Kastak et al., 2007; Kastak et al., 2005).

4.2. Potential effect on marine fish

Although sound is of key importance for almost all vital functions among most marine fauna, sound perception has been studied only for a small percentage of fish species (Ladich and Fay, 2013). To date, around 100 fish and invertebrate species have been shown to be impacted by anthropogenic noise (Slabbekoorn et al., 2010), resulting in decreases in growth (Anderson et al., 2011), immune competency (Celi et al., 2015), productivity (Lagardère, 1982; Stanley et al., 2017), body condition (Bruintjes et al., 2016; Buscaino et al., 2010; Casper et al., 2013a, 2013b), catch rates (Purser and Radford, 2011), anti-predator defence (Spiga et al., 2017), school coordination (Hawkins et al., 2014; Herbert-Read et al., 2017) and cohesion (Kastelein et al., 2017; Neo et al., 2014).

Injuries and lethal effects could be shown for multiple fish species, such as spot, pinfish, lake sturgeon, Nile tilapia, hogchoker and Chinook salmon after exposure to impulsive sounds in the close vicinity of offshore wind farm construction site (Govoni et al., 2008; Halvorsen et al., 2012a, 2012b) and were more likely to affect the swim bladder and surrounding organs than the inner ears (Casper et al., 2013c). Such impairment of hearing or other organs is unlikely in the framework of anchor pipes vibration embedment operations.

Behavioural reactions might be more likely to be evoked. Two fish species displayed significant movement response to a pile driving stimulus at relatively low received sound pressure levels (SPL; sole: 144–156 dB re 1 μPa peak; cod: 140–161 dB re 1 μPa peak, particle motion between 6.51×10^{-3} and 8.62×10^{-4} ms^{-2} peak) (Mueller-Blenkle et al., 2010). Sole showed a significant increase in swimming speed during the playback period compared to before and after the playback. Cod exhibited a similar reaction, yet results were not significant. Cod showed a significant freezing response, i.e. decreasing the swimming speed, at the onset and cessation of playback. There were indications of directional movements away from the sound source in both species. Further, the results showed a high variability in behavioural reactions across individuals and a decrease of responses with multiple exposures (Mueller-Blenkle et al., 2010).

The study of Mueller-Blenkle et al. (2010) did not identify a single threshold, but a range over which behavioural responses occurred for sole and cod. The behavioural reaction threshold range for sole was found to be 126–142 dB re 1 μPa^{2}s, based on the SPL range reported by Mueller-Blenkle et al., 2010. Since this range is given as a SPL, it cannot be referenced to our data directly. The corresponding SEL range was determined by a best linear fit between the recorded SPL vs SEL values. The reported range corresponds to a received SEL at a maximum distance of 132 m (up to 430 m for the SEL_{05}) from the construction site. The behavioural reaction threshold range for cod was 121–149 dB re 1 μPa^{2}s, which corresponds to a received SEL at a maximum distance of 314 m (up to 766 m for the SEL_{05}) from the construction site.

Our results show that these two fish species might be affected by the noise generated from the anchor pipe vibration embedment operations up to a distance of 132 to 766 m from the construction site. Different fish species react very differently to noise and the reaction threshold must not inevitably follow hearing curves. Moreover reactions to anthropogenic sounds depend on the context, meaning for example animal's age, school size, individual body size, water temperature, location or physiological state, and generalisations should therefore be made with great caution (Kastelein et al., 2008).

An increasing amount of anthropogenic noise in the ocean can mask biologically relevant acoustic signals possibly leading to complete or partial loss or misinterpretation of signals. Masking is therefore considered as one of the main effects of noise pollution on marine animals and might alter acoustic communication, impact predator avoidance and prey detection and as a result might have a major effect on whole ecosystems (Slabbekoorn et al., 2010). Acoustic signals of Wadden Sea fish that might be affected by masking can be found in herring (Wahlberg and Westerberg, 2003), sand goby (*Pomatoschistus minutus*) (Lindström and Lugli, 2000), Atlantic cod (Hawkins and Rasmussen, 1978; Rowe and Hutchings, 2005), tub gurnard (*Chelidonichthys lucerna, Trigla lucerna*) (Amorim, 2006), pollack (*Pollachius pollachius*) and tadpole fish (*Raniceps raninus*) (Amorim, 2006; Hawkins and Rasmussen, 1978) (see Table 1). The sound communication in fish in the Wadden Sea might be affected in terms of calling activity (de Jong et al., 2018; de Jong et al., 2016; Putland et al., 2017; Van Oosterom et al., 2016), alteration of sound characteristics (Lombard effect) (Holt

Table 1
Acoustic signals of the Wadden Sea fish.

Species	Latin name	Sound type	Centre frequency	Duration (ms)	Number of pulses	Source level	Reference
Herring	*Clupea harengus*	Pulsed chirp	4.1 kHz	32–133	7–50	73 ± 8 dB re 1 µPa rms	(Wahlberg and Westerberg, 2003)
Sand goby	*Pomatoschistus minutus*	Bursts	100 Hz		23–29	118–138 dB re 1 µPa	(Lindström and Lugli, 2000)
Atlantic cod	*Gadus morhua*	Grunts	~50–500 Hz				(Hawkins and Rasmussen, 1978; Rowe and Hutchings, 2005)
Tub gurnard	*Chelidonichthys lucerna, Trigla lucerna*	Grunts, knocks	~311 Hz	26			(Amorim, 2006)
Pollack	*Pollachius pollachius*	Grunts					(Amorim, 2006; Hawkins and Rasmussen, 1978)
Tadpole fish	*Raniceps raninus*	Grunts					(Amorim, 2006; Hawkins and Rasmussen, 1978)

and Johnston, 2014; Ladich, 2019; Luczkovich et al., 2016) and reduction in detection distance (Stanley et al., 2017).

4.3. Marine strategy framework directive

Germany, as European member state, is obliged to assess the current situation in their waters and to monitor changes in the future to implement the European marine strategy framework directive (MSFD, Descriptor 11, European Union, 2008). In the course of this directive underwater noise is embedded as one of the descriptors (Descriptor 11) and is entitled 'Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment'. There are few studies that provide useful methods on how to assess the impact of underwater noise (Boyd et al., 2008; Faulkner et al., 2018). Compared to the study of Codarin and Picciulin (2015), we also investigated a coastal area exposed to anthropogenic noise. However, their study focused more on ship noise within two third-octave bands (63 Hz and 125 Hz), relevant for chronic exposure to low frequency ambient noise (van der Graaf et al., 2012). We on the other hand, considered the noise exposure within several third-octave bands to figure out in which frequency the sound exposure level was highest. The investigated sound source was an innovative method of fixing anchor pipes at the seabed, therefore the kind of noise had to be identified. Our study can be seen as the a first step of risk assessment, the hazard identification according to the research strategy of Boyd et al. (2008). We however went one step further and presented potential effects on different species in theory without measuring the exposure on the animals.

5. Conclusion

Underwater noise is the most widespread and pervasive kind of anthropogenic energy which is introduced in the marine environment. Our study showed that the detected anchor pipe vibration embedment noise might induce a behavioural reaction in indigenous species from the Wadden Sea on a local scale. The construction of seed mussel collectors was done on certain conditions, for instance the anchor pipes for the seed mussel collectors were vibrated into the seabed as an alternative to pile driving. It can be concluded that the method of vibrating is much less harmful to the marine fauna than pile driving, at least for the species considered in our study. Our study gives an example that a sustainable human use in respect to the complied guidelines, can lead to a harmonious relationship between the needs of society and ecological integrity as conceded by the Trilateral Wadden Sea Plan (2010).

Declaration of Competing Interest

The authors declare no competing financial and/or non-financial interests.

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