CHAPTER 7

WHAT DRIVES HARBOUR PURPOISE (*PHOCOENA PHOCOENA*) RESPONSE TO PILE DRIVING SOUND?

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Abstract

In the southern North Sea, offshore wind farm construction usually requires hydraulic pile driving resulting in high levels of impulsive sound. Despite recent advances in noise-mitigation technology, harbour porpoises (*Phocoena phocoena*) respond to this pile driving over a period of hours to days per driven pile, depending on the distance at which the animals were disturbed. We used passive acoustic monitoring (PAM) datasets from 2018 to 2020, including the construction periods of three offshore wind farms (Norther, Northwester 2 and SeaMade), to determine the factors which influenced the likelihood of detecting harbour porpoise (*Phocoena phocoena*) before, during and following pile driving in the Belgian part of the North Sea (BPNS). During pile driving and in the 24 hours after pile driving, mean detection rates of porpoises reduced up to 20 km from the pile driving location although both the magnitude and duration of this reduction decreased markedly with increasing distance. Generalized Additive Modelling (GAM) found distance to the construction site (as a proxy found received sound level) to be the main driver for porpoise response to pile driving with seasonality, time of day and type of sound mitigation having a limited but significant effect on the spatial and temporal extent of avoidance of the construction area by porpoises. In the immediate vicinity of the construction site, the reduction in porpoise detection rates starts even prior to the pile driving suggesting the presence other sources of disturbance in this area. Our results suggest that efforts to reduce the impact of underwater noise generated by future offshore wind farm construction on marine life should aim to limit not only the noise levels generated but also the overall duration of the construction period.

1. Introduction

The harbour porpoise (*Phocoena phocoena*) is by far the most common marine mammal in the BPNS, after several years of virtual absence (Haelters *et al.* 2011). Despite interannual variation, harbour porpoises show a distinct spatial and temporal distribution in Belgian waters with relatively high densities from January to April and lower numbers from May to August, plus they tend to concentrate in more northerly and offshore waters (Haelters *et al.* 2011, 2016; Augustijns 2018). The animals present in Belgian waters do not form an isolated population, but are part of a much larger population, which extends into the southern and central North Sea. In the greater North Sea, the harbour porpoise is considered vulnerable because of high bycatch levels (Kaschner 2003) and its exposure to increasing levels of noise pollution ranging from continuous shipping noise (Wisniewska *et al.* 2018) to impulsive noise from, e.g., pile driving (Brandt *et al.* 2018), and seismic surveys (Van Beest *et al.* 2018). Nonetheless, the species is protected by both national (Belgian Government 2001) and EU law (European Union 1992), and consequently deliberate actions of killing, disturbing, injuring, or habitat deterioration are prohibited throughout its range. In the absence of mitigating measures, the high levels of impulsive underwater sound generated during pile driving can potentially kill, injure and disturb marine mammals depending on their distances from the source (see, e.g., Carstensen *et al.* 2006; Bailey *et al.* 2010) with some studies indicating potential negative cumulative impacts on the harbour porpoise population the North Sea as a result of planned wind farm development over the next decade (de Jong *et al.* 2019).

In order to meet the EU objective of reaching net-zero greenhouse gas emissions by 2050, offshore wind capacity in the North Sea should increase to a total installed capacity of 260 GW by 2050, with intermediate targets of at least 76 GW by 2030 and 193 GW by 2040 (North Seas Energy Cooperation 2022). Concerns over the possible impact of high intensity impulsive sound generated during the construction of these offshore wind farms on harbour porpoise have been a driving force in determining national impulsive noise regulations in North Sea countries with Germany, the Netherlands and Belgium all formulating different, but similar, underwater sound thresholds (see Rumes *et al.* 2016 for a comparison). In Belgium, this concern over the high levels of underwater noise being generated during pile driving operations for the building of the first offshore wind farms (Norro *et al.* 2010, 2013) and the observed large-scale avoidance of the construction zone by porpoises (Haelters *et al.* 2011, 2013) led to the formulation of strict mitigating measures which included both seasonal pile driving restrictions (Rumes *et al.* 2013), and a threshold for impulsive underwater sound in the Belgian part of the North Sea (BPNS) at 185 dB re 1 μPa (Sound Pressure Level, zero to peak) at 750 m from the source (Anonymous 2012). This led offshore wind farm developers in the BPNS to apply noise mitigation systems which made incremental progress in complying with the national threshold (Rumes & Degraer 2020). When effective noise mitigation was applied, reductions to the spatial and temporal extent of avoidance of the construction area by porpoises were observed (Rumes & Zupan 2021). Nonetheless, and especially in the immediate vicinity of the pile driving site, a prolonged reduction in porpoise detection rates was observed.

In this chapter, we applied a GAM model to data from the construction of three wind farms to determine the factors which influence the observed spatial and temporal extent of harbour porpoise avoidance during pile driving and thereby provide an improved basis for formulating effective mitigating measures.

2. Material and methods

2.1. Study area and sites

The Southern Bight of the North Sea includes the BPNS with a surface of approximately 3450 km^2. The BPNS only covers 0.5% of the entire area of the North Sea and is characterized by shallow waters with a maximum depth of 45 m and a complex system of sandbanks. In 2004, in the western part of the BPNS, a 264 km^2 zone was designated for renewable energy. In 2011, this zone was adjusted on its Northern and Southern side to ensure safe shipping traffic thereby reducing the area to 238 km^2. Between 2009 and 2020, nine projects have constructed wind farms in this part of the BPNS.

For this study we focused on three wind farms constructed between 2018 and 2020: Norther, Northwester 2 and SeaMade (Figure 1).

Norther NV obtained an environmental permit on January 18th 2012 to build and operate its offshore wind farm. The windfarm was built at a distance of 20 km from the coastline to the south of the Thornton bank. The total capacity of this wind farm of 370 MW is provided by 45 turbines, each with a capacity of 8.4 MW. Pile driving for the Norther wind farm comprised 45 piling events from June 8th up to November 12th, 2018. Pile diameter ranged from 7.2 to 7.8 m, penetration depth lay between 24 to 47 m and total piling time varied between 52 min and 3h43 min. All piles were installed using an S-3500 Hydraulic Hammer (maximum energy per pile 3028 ± 456 kJ). The contractor was legally obliged to turn on an acoustic deterrent device one hour before the start of piling. Construction logs show that the acoustic deterrent device was often switched on much earlier, in casu between 60 to 490 minutes (on

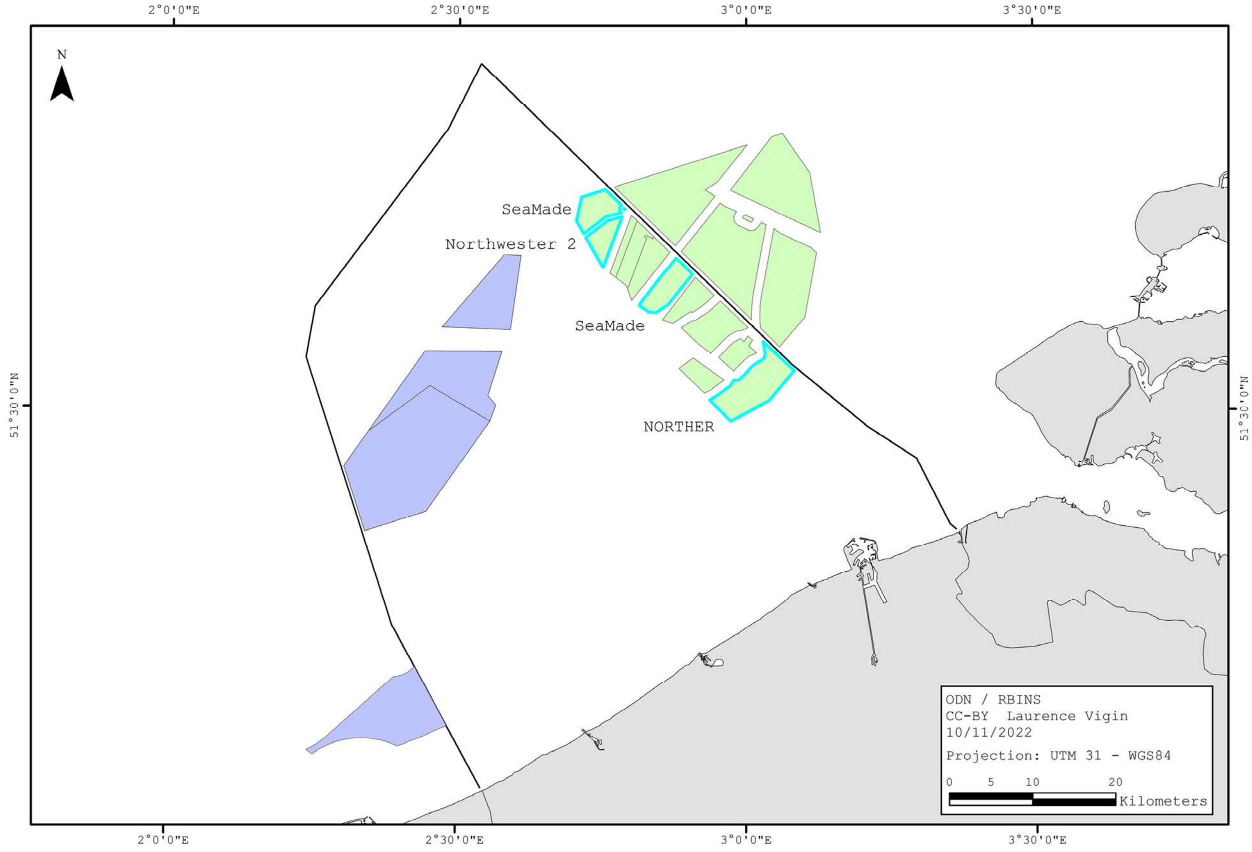

Figure 1. Operational (green) and planned (blue) offshore wind farm zones in the Belgian part of the North Sea and adjacent Dutch and French waters showing the location of the three wind farms constructed between 2018 and 2020: Norther, Northwester 2 and SeaMade.

average 150 minutes) before the start of pile driving (Rumes & Degraer 2020).

The second wind farm, NV Northwester 2, is located at 51 km off the coast of Zeebrugge to the northwest of Nobelwind, was granted an environmental permit on 18 December 2015. The total capacity of this wind farm of 219 MW is provided by 23 turbines, each with a capacity of 9.5 MW. Pile driving for the Northwester 2 wind farm comprised 24 piling events (23 turbines and one offshore high voltage station) from July 29th up to November 13th, 2019. Pile diameter ranged from 7.4 to 8.0 m, penetration depth lay between 29 to 39 m and total piling time varied between 1 h 36 min and 3h40 min. All piles were installed using an S-3000 Hydraulic Hammer (maximum energy per pile 1942 ± 406 kJ). The contractor was legally obliged to turn on an acoustic deterrent device 30 minutes before the start of piling. Construction logs show that the acoustic deterrent device was switched on between 32 to 342 minutes (on average 66 minutes) before the start of pile driving (Rumes & Degraer 2020).

The third wind farm, SeaMade, is comprised of two separate sections located at 40 and 54 km off the coast of Zeebrugge and was granted an environmental permit on 13 April 2015. The total capacity of this wind farm of 487 MW is provided by 58 turbines, each with a capacity of 8.4 MW. Pile driving for the SeaMade wind farm comprised 60 piling events (58 turbines and two offshore high voltage station s) from September 8th, 2019, up to January 2nd, 2020. Pile diameter ranged from 7.5 to 8.0 m, penetration depth lay between 27 to 41 m and total piling time varied between 1h5 min and 3h26 min. All piles were installed using an S-4000 Hydraulic Hammer (maximum energy per pile 1930 ± 423 kJ). The contractor was legally obliged to turn on an acoustic deterrent device 30 minutes before the start of piling. Construction logs show that the acoustic deterrent device was switched on between 24 to 185 minutes (on average 42 minutes) before the start of pile driving (Rumes & Degraer 2020).

All three wind farms used hydraulic pile driving to install monopile foundations. At Norther, pile driving using a single big bubble curtain (SBBC) took place in 2018. A SBBC consists of one ring of perforated pipes positioned on the sea floor around the foundation to be piled. Compressors located on the construction vessel or on a separate platform feed air into the pipes. The air passes into the water column by regularly arranged holes. Freely rising bubbles form a large curtain around the entire structure, thus shielding the environment from the noise source (Koschinski & Lüdemann 2013). Noise reductions of 10-15 dB SEL have been found for SBBC (Bellman *et al*. 2015). In a DBBC, used at Northwester 2 and SeaMade, a second ring of perforated pipes is positioned on the sea floor around the foundation to be piled which, according to Bellman *et al*. (2015) should result in additional noise reduction of ~3dB (or a further halving of the noise emissions). Northwester 2 was the only project to successfully use noise mitigation measures that limit the transmission of noise pollution to the marine environment to the extent that the in-situ measured sound level (SPL_{z-p}) remained below the national threshold of 185 dB re 1 μPa at 750 m from the source (Norro 2020). Other measures taken with the aim of reducing the impact of pile driving on harbour porpoise included the use of an ADD to deter porpoises from the immediate vicinity of the construction site and the obligation to halt pile driving when a porpoise is detected near the construction site (see Rumes *et al*. 2020 for an overview).

2.2. Study set up

Harbour porpoises use echolocation for navigation, foraging, and social communication (Berta *et al*. 2015; Au 2018; Read 2018). This makes it their most important sensory perception and they have been shown to use this echolocation system almost continuously (Akamatsu *et al*. 2007; Wisniewska *et al*. 2016). This allows a correlation between detection rates of porpoise clicks by passive acoustic monitoring devices and porpoise density in a marine area. Passive acoustic monitoring of porpoises was conducted using the Continuous Porpoise Detector (C-PoD, further indicated as PoD). PoDs consist of a hydrophone, a processor, batteries and a digital timing and logging system. They continuously monitor sounds between 20 kHz and 160 kHz, and can detect all odontocetes except sperm whales (*Physeter macrocephalus*). A PoD does not record sound itself, but stores the sound parameters of each click instead, such as time of occurrence, duration, dominant frequency, bandwidth and sound pressure level. Using dedicated software (CPOD.exe,; Tregenza 2014), the clicks are processed and a detector generates click trains which are then classified into trains produced by odontocetes and trains that originate from other sources such as boat SONAR. Distinction can be made between harbour porpoises, a species producing narrow-band, high frequency clicks, and dolphins, producing more broadband clicks with a lower frequency. The maximum detection range for porpoises is approximately 400 meters. PoDs have autonomy of up to 200 days (www.chelonia.co.uk). As porpoise click sounds are emitted in frontal direction with a beam angle of 16.5° maximum (Au *et al.* 1999), PoDs are only able to detect porpoises if they are facing towards the hydrophone.

For this study, we used data from PoDs deployed at 19 locations in the BPNS: 11 of which were specifically deployed for this study and the other 8 are part of the Cetacean passive acoustic network, (Flanders Marine Institute 2021). PoD locations need to be visited every 3-4 months to replace the batteries and memory card. This was not always possible due to logistical issues (incl. COVID-19) leading to gaps in the dataset. In addition, certain mooring locations were changed over time in function of ongoing construction activities.

2.3. Data selection and dataset preparation

PoD data (merged high and moderate quality click train detections) were downloaded via LifeWatch data R package (Flanders Marine Institute, 2021; ; Hernandez *et al.*, 2021). The selected PoD data ranged from the 1st of July 2018 to the 30th of June 2021. Detections were aggregated per hour to Detection Positive Hours (i.e., 0/1; DPH). We only used data where the PoD recorded a full hour (60 minutes). Minutes where the number of clicks exceeded the upper detection limit (4096 clicks per minute) were removed from the dataset. As in Brandt *et al* (2016), hourly data was disregarded when data for more than two minutes needed to be removed. In total, 53 % of the original hourly data was kept.

At least 30 minutes before pile driving an ADD is to be activated in order to deter porpoises from the immediate vicinity of the construction site and to protect them from the acute effects of construction noise. However, due to operational uncertainties, the actual interval between ADD activation and the start of pile driving is quite variable (Rumes & Degraer 2020) and for these analyses, the start of pile driving was provided by the developers in daily reports on piling activities. As in Brandt *et al.* (2016), hours when deterrence took place before or after the piling itself were excluded from the dataset in an attempt to exclude the effects of acoustic deterrence devices on porpoise presence (Figure 2). To align the (per hour) DPH information on detections with the (per minute) information on pile driving, the latter was rounded to the nearest hour, and for each hour the following information was generated: time relative to the acoustic disturbance in hours and location of the most recent disturbance. We calculated the minimum time since acoustic disturbance (in hours) per PoD station and per hour and combined it with the information on the distance to the individual piling events.

2.4. Modelling

Hourly Porpoise presence was modelled with the goal of identifying patterns in the porpoise presence before, during and after pile driving in the BPNS (Table 1). A Generalized Additive Model (GAM) was

Table 1. Variables tested for incorporation into the model (variables retained in the final model are indicated with *).

Variable	Type	Description
Pile driving related		
Distance*	Thin plate regression spline	Distance between a piling event and its respective PoD station
Pile Project*	Random effect	A combination of Pile ID and Project
Relative Time*	Thin plate regression spline	Hour relative to the piling event (ranging from -48 to +120)
Sound Mitigation*	Fixed effect	Type of sound mitigation used for the respective piling event
Time-related		
Hour	Cyclic cubic regression spline	Hour of the day
Month*	Fixed or random effect	Month of the year (1-12)
Space-related		
Latitude Receiver*	Random effect	Latitude coordinates of the receiver
Longitude Receiver*	Random effect	Longitude coordinates of the receiver
Interaction		
Distance & Relative Time*	Interaction smoother	Interaction smoother between Distance and Relative Time
Hour by month*	Cyclic by fixed effect	Hour spline is redefined per level of the month

All data analyses were performed in R version 4.2.1 (R Core Team 2022).

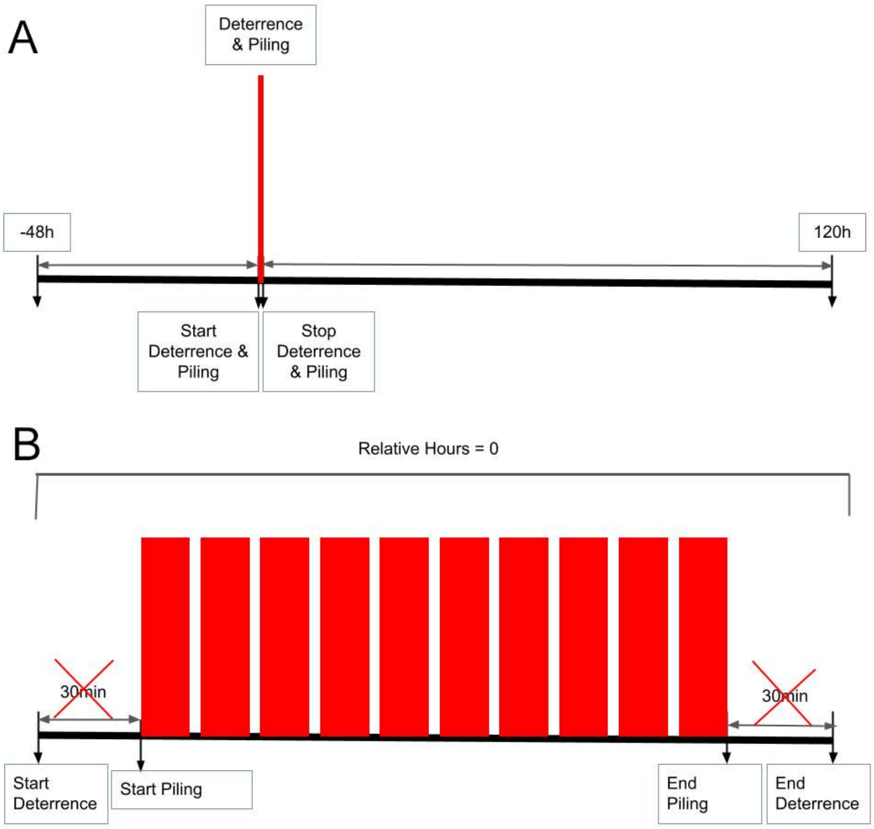

Figure 2. A. Schematic of the timeline displaying how the relative times of the hours before, during and after one pile driving event are implemented. **B**. The pile driving event itself. The moments of deterrence before and after pile driving are crossed out to indicate that these were excluded from the model data.

fitted and evaluated using the R package mgcv, version 1.8.40 (Wood 2017). Both piling- and noise-related variables (to account for noise exposure and applied mitigation) were included. Time-and space- related variables were added to account for temporal autocorrelation and inherent temporal and spatial patterns such as seasonality and habitat suitability. The Akaike information criterion (AIC) was be used as a guide to decide on the best suitable combination of these variables. More complex models were disregarded in favor of simpler models if the more complex model didn't result in a meaningful improvement in AIC (see De Pauw 2022 for a detailed overview of the models tested and their AIC-scores).

In our dataset, pile driving events only occurred from July to early January, and thus the full effect of seasonality on porpoise response to pile driving will not be incorporated into the models. However, porpoise seasonal occurrence in the BPNS is known vary greatly between July and January (Haelters *et al*. 2016; Augustijns 2018), and thus it is justified to incorporate the month as a proxy for seasonal effect in the models.

3. Results

Nearly all tested variables were incorporated into the final GAM model which had the lowest AIC value (Table 1). The smooth and parametric effects of the selected model are shown in Figure 3. Note that effects are not

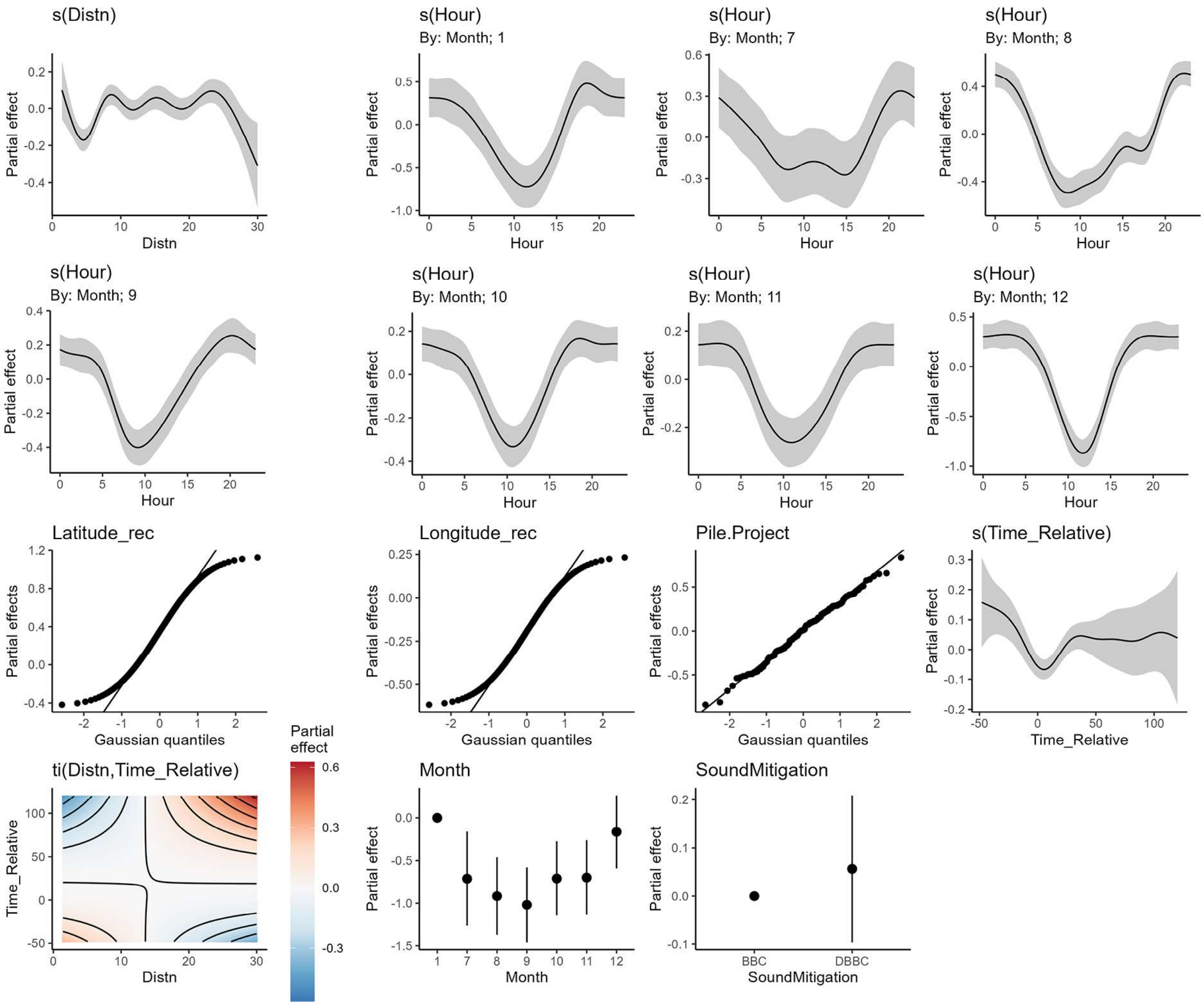

Figure 3. Model smooth and parametric effects.

absolute but relative, as the smoothers are centered to ensure identifiability of the model.

The effect of Hour of the day (per month) reflects the known diel pattern of porpoise activity in Belgian waters and its seasonal changes (see Augustijns *et al*. 2018).

The seasonal effects, which are shown by the month partials, show the known decline in presence over the summer months.

The partial effect of Sound Mitigation shows a lot of variation and almost no difference in effects with DBBC scoring on average only slightly better than SBBC. It should be noted here that the degree in success of DBBC application varied significantly between different projects (see Norro 2020).

Due to the presence of an interaction smoother, the effects of Relative Time and Distance can only be evaluated in combination. The relative combined effect of Distance, Relative Time and their interaction term is shown in Figure 4A. Before the pile driving takes place (-48h to ~-4h), a positive combined effect can be seen on porpoise detections across all distances. The decrease in effect on porpoise detections can be noticed during and to a limited extent shortly before the pile driving (at Relative Time = ~-4h -0) this decrease tends to be less pronounced at larger distances from the source (from ~20 km). After pile driving, this negative effect continues at small distances (< 10 km), but relatively quickly (~12h) bounces back to a positive effect for longer distances (> 10 km).

Figure 4B shows that most of the observations occur during pile driving. There are also more frequent observations 48 hours after the piling than 48 hours before the piling. Two reasons for the lower number of observations in the hours before the pile driving are 1) the rule that baseline hours (before pile driving) were only counted if at least 48 hours had passed from the previous piling event which was relatively rare, 2) due to the exclusion of hours with ADD use (see 2.3).

The uneven spread of the data is also the likely cause for the wiggly nature of the modelled effect of Relative Time and Distance. The used thin plate regression splines will be anchored by dense regions of data, and the polynomial nature of those splines allows the response surface to wiggle between those anchor points. The used penalty terms in the fitting process are not sufficient to dampen

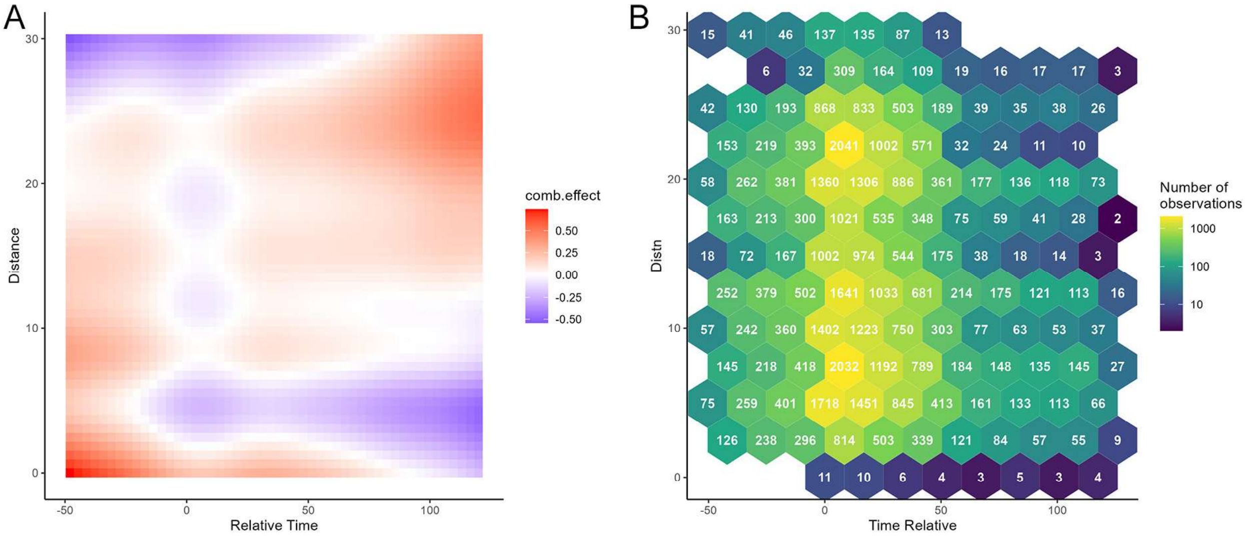

Figure 4. Comparison of combined effect of Distance from the sound source and Time Relative to pile driving on porpoise detection positive hours (Dph) (A) with their respective amounts of datapoints (B). **A**. Combined effect Time Relative and Distance on Dph. **B**. Number of recorded hours spread through Time Relative and Distance (Distn).

Table 2. Variance components of the random effects of the model with all random effects included.

Component	Variance	Standard deviation	Lower Confidence Interval	Upper Confidence Interval
Latitude Receiver	0.0846	0.291	0.0725	1.170
Longitude Receiver	0.0233	0.153	0.0378	0.616
Pile Project	0.1340	0.365	0.3140	0.425

this effect when the data is spread unevenly. Hence the model output should be interpreted with care in the most general terms.

Table 2 shows the variance of the three random effects in the model. Pile Project has the highest variance, which implies that between the piling events there is more variance on the effect on porpoise presence than that of the spatial variance explained by Latitude and Longitude of the receiver.

4. Discussion

4.1. Key model findings and consequences for effective mitigation of impulsive underwater sound

After correction for other sources of variation, the GAM model predicts a moderate reduction in odds for detection of porpoises during pile driving compared to 48 hours before pile driving at distances up to 20 km from the source (Figure 4A). This relative decline becomes less marked with increasing distance from the piling event. This is in line with porpoise response to lower levels of pile driving sound (Rose *et al.* 2019). From 25 km onwards the model hints at an opposite effect, with relatively more detections after pile driving than before pile driving. Dähne *et al.* (2013) reported a similar increase in detections beyond 25 km and suggested that this could be due to the displacement of affected porpoises towards these areas. However, due to the limited availability of data (see Figure 4B), effects beyond 20 km are predicted with large uncertainties and hence should be interpreted with care.

At distances up to around 5 km from the piling event, the model also showed a reduction in porpoise detections starting several hours before the piling event. As previously suggested, this could be due to elevated levels of shipping noise and other preparatory works (Brandt *et al.* 2016; Rumes *et al.* 2017; Rumes & Zupan 2021).

At these lower distances, the effect remains negative for the entirety of the modelled period (up to 120 hours after the piling event). As data becomes scarce when the piling event is further away in time, trends after 48 hours are modelled with large uncertainties and hence should be interpreted with caution. A possible explanation for the extended negative effect could be that due to consecutive piling events porpoises learn to avoid the wind farm construction zone, as argued in Rumes *et al.* (2017). However, it could also be linked to the seasonality of porpoise distribution in Belgian waters (Haelters *et al.* 2016) and the uneven distribution of pile driving events with longer intervals between subsequent pile driving events (which are more often observed at the start of the construction period, here: in periods of lower porpoise densities). In general, effects of seasonality and time of the day on the likelihood of detecting porpoises aligned well with known information on porpoise behavior (Augustijns *et al.* 2018) and seasonality (Haelters *et al.* 2011) in Belgian waters.

The type of sound mitigation used does not seem to have an effect according to our model (Figure 3). It is unclear whether this is due to the difference in sound mitigation between SBBC and DBBC being only in the order of a few dB (Bellman 2014) or because of the uneven way in which the latter sound mitigation technique was applied (Norro 2020). In this study all pile driving events were accompanied by some form of sound mitigation, which made it impossible to study the effect of sound mitigation on harbour porpoises' response to pile driving per se. Previous studies have shown the effects of unmitigated pile driving on porpoise to reach much farther (26 km [s.e.: 22-30 km]) than those of mitigated pile driving (11 km [s.e.: 10-12 km]) (Rose *et al.* 2019; Rumes *et al.* 2021).

4.2. Limitations to the current study and future work

Even though AIC is a well-known model selection criterion it also comes with some disadvantages. It only measures the relative quality of a model, so even though AIC tells which model fits better, the best model could still fit the data poorly (Zajic 2019). Furthermore, the lack of a framework for formal hypothesis testing doesn't allow to decide whether the improvement in AIC is substantial enough to be relevant. Alas, the complexity of GAM incorporating random terms doesn't allow to use, e.g., likelihood-ratio tests typically used with GLMs for this purpose. Hence, choosing between models solely on AIC score remains a fairly subjective matter. For our model, effects beyond 20 km should be interpreted with care, as only limited data was available at these distances (see Figure 4B) which can result in artifacts of the smoother.

As noted previously (Rumes *et al.* 2017), even during pile driving, harbour porpoises are not completely absent from sites in the vicinity of pile driving. Lacking information on the movement on individual porpoisesand the amount of underwater sound these animals are exposed to, it is impossible to draw conclusions about causal relationships based on the presented model. Detections in the vicinity of the construction zone can be due to both the continued presence of animals which tolerate higher levels of underwater sound and animals which are moving away from the sound source. A future comparison of the proportion of feeding buzzes to total porpoise click trains (sensu Nuuttila 2013; Zein *et al.* 2019) during and after acoustic disturbance can provide more information on their response to acoustic disturbance.

In the last 20 years ~25 GW of offshore wind has been constructed in the North Sea (WindEurope 2021). Over the next 20 years, construction rate is expected to increase nearly tenfold resulting in an increased exposure of marine life to harmful levels of impulsive underwater sound from wind farm construction. Avoiding potential negative cumulative impacts on local cetacean populations will require coordinating construction efforts and/or formulating coherent mitigation measures at North Sea scale. Current mitigation efforts vary strongly between individual countries, but, in general, have focused on reducing transmission and the lowering of sound levels of individual pile driving events to comply with national impulsive noise regulations for impulsive underwater sound. Our results show received sound level (here distance of the PoD to the construction site) to indeed be the main driver for the magnitude of the porpoise response to pile driving. However, the relatively long duration of disturbance (and consequent reduction in porpoise detections) in the vicinity of the construction site (< 10 km) highlights the potential environmental benefits of measures aimed at a) reducing the overall duration of the construction period (e.g., by installing fewer foundations or further reducing the time between piling events) b) avoiding pile driving during periods with elevated porpoise presence (e.g., by implementing a seasonal pile driving ban).

Acknowledgements

The authors would like to thank the crews of RV *Belgica*, RV *Simon Stevin*, and the *Zeetijger* for help during deployment and collection of the PAM devices. Laurence Vigin is thanked for her help with the map. The collaboration and support of the windfarm operators is greatly appreciated. The data for this study were obtained from the RBINS wind farm monitoring programme and were provided by VLIZ as part of the Flemish contribution of the LifeWatch ESFRI funded by the Research Foundation—Flanders (FWO).

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