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RESEARCH ARTICLE

Echolocation activity of harbour porpoises, *Phocoena phocoena*, shows seasonal artificial reef attraction despite elevated noise levels close to oil and gas platforms

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Abstract

1. Harbour porpoises frequently alter their behaviour in response to underwater sound from shipping, seismic surveys, drilling and marine renewables. Less well understood is the response of porpoises to sounds emitted from oil and gas (O&G) platforms during routine operations.
2. The responses are not easily predicted as platforms can act simultaneously and to varying degree as a source of disturbance through noise and attraction through an artificial reef effect with increased prey abundance and diversity.
3. To investigate the presence and feeding behaviour of harbour porpoises around platforms, autonomous acoustic loggers were placed for up to 2 years, at 21 stations 0–25.6 km from the largest platform in the Danish North Sea.
4. Harbour porpoises were detected at all distances year round in two distinct seasonal activity patterns. During July–January, porpoises were attracted to the platform as indicated by high foraging activity within 800 m of the platform. Echolocation activity levels were up to twofold higher than those observed at 3.2–9.6 km from the platform.
5. Similar high echolocation activity was observed 200 m from neighbouring offshore installations located within 15 km, regardless of their size, during May–July.
6. This study shows that porpoises may be attracted to offshore O&G platforms despite confirmed elevated underwater noise and are likely exploiting higher prey abundance in the vicinity of such structures. This is possibly due to increased prey availability created by the combined effect of the artificial reef formed by the underwater structure and the local protected area around all platforms where fishery is banned.
7. Hard substrate and untouched seabed are rare and valuable habitats to many organisms in heavily trawled waters like the North Sea, and the ecological importance of these structures should be considered in the development of decommissioning strategies.

KEYWORDS
biodiversity, decommissioning of oil and gas platforms, foraging, hard substrate, North Sea, passive acoustic monitoring, porpoise detector C-POD, underwater noise

1 | INTRODUCTION

Since North Sea oil and gas (O&G) production started more than 40 years ago, over 1450 structures have been installed in the region (https://www.ospar.org/work-areas/oic/installations; Figure 1). As many of these offshore O&G structures are coming to the end of their operational lives across the North Sea, the ecological roles of these structures in the regional marine environment remains to be understood to be integrated in assessment of net environmental benefit of the diverse decommissioning strategies (Birchenough & Degraer, 2020; Fortune & Paterson, 2020; Fowler et al., 2020). Offshore structures act as artificial reefs by providing local protected habitats for predators and their preys and have led to the implementation of the rig-to-reef concept which consists of leaving some parts of the O&G structure (i.e. platform legs) in place beyond its operational lifetime (Birchenough & Degraer, 2020; Macreadie et al., 2012). This practice has been quite popular in the United States and in particular in the Gulf of Mexico, where several hundreds of O&G platforms have been left permanently with net environmental benefits and added societal benefits for fisheries and recreational diving (Birchenough & Degraer, 2020).

In the North Sea, OSPAR decision 98/3 on the disposal of disused offshore installations generally prohibits leaving any in situ above ground structure in the North East Atlantic region (OSPAR 1998/3). Yet, several studies have shown that North Sea O&G structures act as artificial reefs and can perform important local and regional ecological roles as natural reefs do (e.g. increasing biodiversity and promoting ecological connectivity; Coolen et al., 2020; Schutter et al., 2019; Tidbury et al., 2019). Based on connectivity modelling, Tidbury et al. (2019) estimated that up to 60% of North Sea marine species connectivity could be broken if all O&G structures were removed. Abundance of North Sea fish species like cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*) have been found to correlate with offshore structures including O&G platforms (Wright et al., 2020). There are indications that, ultimately, O&G structures attract North Sea top predators such as sharks and marine mammals (Todd et al., 2016), including harbour porpoises (Delefosse et al., 2017). Recognizing the potential importance of this artificial ecological network for this region, it is important to assess the net environmental benefits of the systematic removal of O&G structures currently in force in the North Sea. Several large-scale projects are investigating this topic for a broad range of invertebrates, fish and marine mammals (e.g. Bakke et al., 2018). Here we focus on how harbour porpoises are distributed in a mature and active O&G activity area in the Danish Central North Sea where they are most common and are protected under the habitat directives.

Harbour porpoises are known to be attracted to hard structures in the sea, but also to change behaviour or avoid areas in response to noise emitted during offshore activities such as seismic surveys, shipping and pile driving (Dyndo et al., 2015; Mikkelsen et al. 2019; Sarnocinska et al., 2020; Thompson et al., 2013; Tougaard et al., 2009; Wisniewska et al., 2018). Sources of underwater noise associated with O&G platforms include production and processing equipment (e.g. pumps, generators, turbines), discharge of produced or cooling water, drilling rigs, stand-by vessels, vessels or helicopters used for transporting personnel and supplies and equipment associated with maintenance operations. As O&G operations continue around the clock, the noise level is expected to be continuously elevated around active platforms. However, few studies have quantified underwater noise generated from operations associated with O&G production (Blackwell & Greene, 2006; Blackwell et al., 2004), and even fewer the relationship between such noise and the presence of marine mammals (e.g. Blackwell et al., 2017). O&G platforms both offer hard structure and emit noise. Whilst it remains unknown how the noise affects the animals, and whether such observations are indicative of generally higher densities close to offshore constructions, evidence suggests that the platforms may attract marine predators (e.g. Mikkelsen et al., 2013; Russell et al., 2014; Todd et al., 2016, 2018).

If O&G activities deter harbour porpoises, then echolocation activity should be lowest close to the platforms and increase with distance from the sound source (Prediction 1). Alternatively, if offshore platforms act as artificial reefs or a small marine protected area, where the motivation to forage is higher than the potential discomfort from elevated noise levels, then echolocation activity should be highest close to platforms and decline or remain stable with increasing distance from platforms (Prediction 2). Here, we tested these predictions by recording the acoustic presence and echolocation behaviour of harbour porpoises along with noise levels at several recording stations deployed around well-established O&G structures in the Danish part of the North Sea.

2 | MATERIALS AND METHODS

2.1 | Study site and experimental design

Acoustic monitoring was carried out from July 2013 to July 2015, to record noise levels and harbour porpoise echolocation activity around DanF, located 200 km west of Denmark (Figure 1). The study area is characterized by sandy sediments and relatively flat bathymetry ranging between 40 and 46 m (Figure 2; Delefosse et al., 2017). Around all Danish O&G installations, a 500-m fishing exclusion zone is enforced, which corresponds to an area of approximately 1.9 km^2 around DanF. To investigate spatial variation in porpoise echolocation activity, 18 acoustic monitoring stations were deployed around DanF at various distances and with replicates along two transects for most distances to

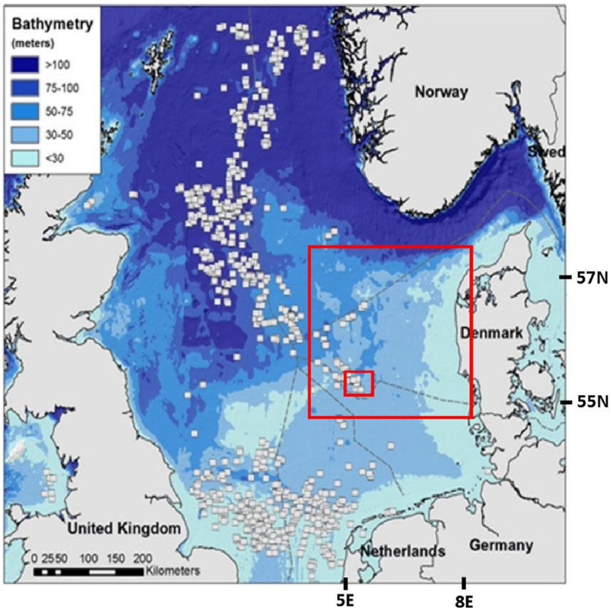

FIGURE 1 Overview map of more than 1450 operational offshore O&G structures in the North Sea (51°–61° N), with an approximately equal proportion of subsea and above water structures (https://www.ospar.org/work-areas/oic/installations). The study area is indicated with the small red square (panel A in Figure 2). The large red square delimits the area for which porpoise densities were modelled (see panel B–D in Figure 2)

avoid data loss (2 × 0 m, 2 × 0.2 m, 2 × 0.4 km, 2 × 0.8 km, 2 × 1.6 km, 2 × 3.2 km, 2 × 6.4 km, 9.6 km, 12.8 km and 2 × 25.6 km; Figure 2). Station locations were chosen to avoid overlap with other O&G installations and minimize variation of environmental factors (e.g. depth). The station located at 12.8 km was placed at Regnar, an inactive subsurface wellhead with dimensions 7.5 m x 6.5 m x 4.5 m that may act as an artificial reef, but does not emit any sound. One station was placed at 25.6 km from DanF as a control stations for the central North Sea (no reef effect and no noise from platforms are present; note that only six months of data are available, Table S1 in the Supporting Information). At all stations, harbour porpoise presence was monitored using acoustic porpoise detectors C-PODs (Chelonia Ltd, Penzance, UK); these are calibrated acoustic click detectors (Clausen et al., 2018). Furthermore, five stations (0, 0.2, 0.8, Regnar and 25.6 km away from DanF) were equipped with calibrated broadband loggers (SM2M+ or SM3M+, Wildlife Acoustics, Boston, MA, USA) to record noise emitted from the platform and other sources in the area. All equipment was deployed 2–3 m above the seafloor with the hydrophone pointing upwards to cover the entire water column. The potential effect on echolocation and noise recordings of instruments being placed near the bottom was considered insignificant (see Supporting Information).

To verify findings from DanF and Regnar, we used data from C-PODs deployed at 200 m from three other platforms during May–June 2014 (HalfdanB, Skjold and Kraka; Figure 2). Together with DanF and Regnar, the three platforms represent a relatively wide range of sizes, industrial activity, light and sound level typical of O&G installations in the shallow (<100 m) central North Sea (seabed footprint of 93—6996 m^2, from small to large: Regnar – only subsea, Kraka – small and unmanned, Skjold, HalfdanB and DanF – large manned platforms with light; Delefosse et al., 2017).

2.2 | Data analysis: Porpoise detections

C-POD data were processed with CPOD.exe v2.043. Following Clausen et al. (2018), the click train filter was set to include click trains with a minimum of five clicks and a mean instantaneous frequency between 100 and 160 kHz, to exclude transient erroneous clicks from unknown sources. Data were exported as porpoise positive minutes (%PPM; i.e. a minute where at least one click train is detected). In addition, all occurrences of click trains with inter-click-intervals (ICI) shorter than 15 ms were extracted. Whilst such short ICIs have been shown to mediate social communication in porpoises (Sørensen et al., 2018), they are more frequently characteristic of echolocation buzzes (74% vs. 26%; Sørensen et al., 2018), which are used during prey pursuits (Verfuss et al., 2009; Wisniewska et al., 2016). We therefore assume that the majority of such click trains are a measure of foraging effort, and they are presented here as buzzing positive minutes (BPM).

Only full recording days (1440 min) were considered in spatial and temporal analyses. The instruments were set to stop recording when the per minute click count reached a maximum of 4095 clicks to avoid memory overload. Due to this truncation, minutes with more than 4095 clicks were excluded from the analysis, as they were considered saturated and incomplete. Each minute within 24 h was assigned to either 'day' or 'night' using civil twilight (http://aa.usno.navy.mil). To reduce any potential influence of an unbalanced data design, only C-PODs with data from a minimum of 3 days within a month were included in the analyses.

We initially explored spatial (distance to platforms) and temporal (diel to month-to-month scale) patterns in porpoise echolocation activity using generalized additive mixed models (GAMM; see the Supporting Information). Based on these preliminary results, we found two distinct porpoise activity periods and therefore grouped data from February–June and July–January.

We then calculated the percentage of %PPM for day and night (D/N) conditions at all stations for the two identified periods separately. The percentage of %PPM was logit-transformed to fulfil the assumption of normality of residuals (Warton & Hui, 2011) and analysed using linear mixed effects models (one model for each period; R Development Core Team 2019) with the interaction between distance to platform and D/N conditions classed as fixed effects. For all mixed models (here and below), C-POD ID, transect ID and year were fitted as nested random effects. Temporal dependence among observations was modelled using an autocorrelation structure of order 1 (corCAR1), because this structure provided the best model compared to other correlation structures based on lowest AIC (Pinheiro and Bates 2000). Moreover, for all mixed effects models constructed, any significant differences in the response variable between and within fixed effects groups were estimated using the Bonferroni-corrected Tukey honest significant difference test.

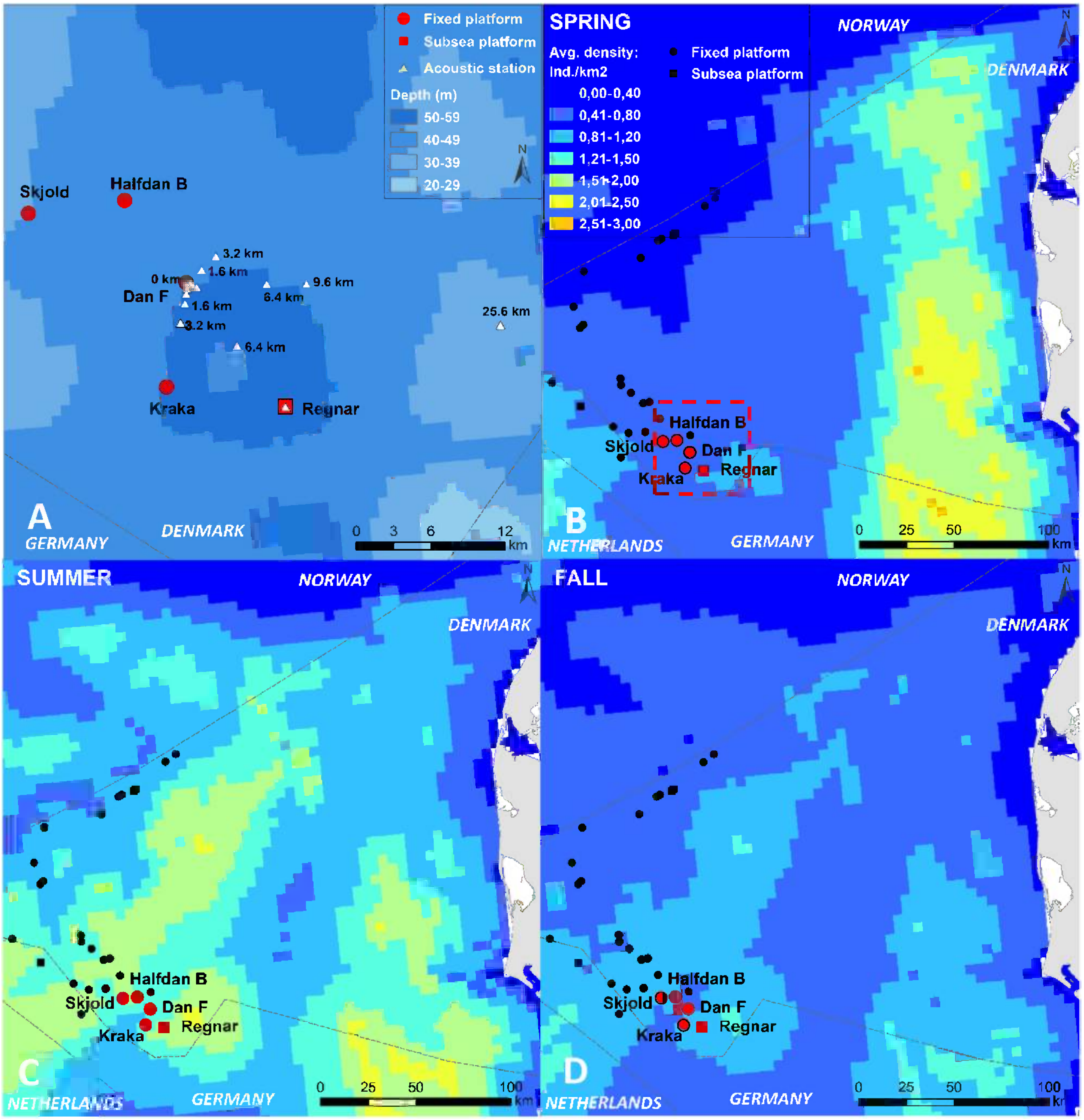

FIGURE 2 The study area around DanF, the adjacent platforms, and the position of the acoustic recording stations are shown in panel A (area equivalent to the dashed square in panel B). Panels B–D show the study area superimposed on harbour porpoise seasonal (Spring: March–May, Summer: June–August, Fall: September–November, no data from winter are available) density obtained from models on available survey data (modified from Gilles et al., 2016)

We computed the percentage ratio of BPM to %PPM (i.e. percentage of time with echolocation clicks that was dedicated to buzzing) for D/N at all stations for the two identified periods separately. To simplify interpretation of the results, stations were grouped as follows: ≤800 m from DanF (the platform), 6.4 km from the platform (control), Regnar (12.8 km from platform) and 25.6 km from the platform (control), for this analysis the other distances were excluded to make a simple comparison between platforms versus control stations. These station groups were, a posteriori, identified as representing 'reef/platform noise', 'no reef/ low platform noise', 'reef/no background noise' and 'no reef/no background noise', respectively. The percentage of BPM/%PPM was logit transformed to fulfil the assumption of normality of residuals and analysed using linear mixed effects models (one model for each period) with an interaction between distance and D/N conditions as fixed effects.

For inter-platform comparison, we calculated the %PPM for each day of May, June and July 2014 using data recorded at 200 m from the five platforms and at a control area (6.4 km from DanF). The

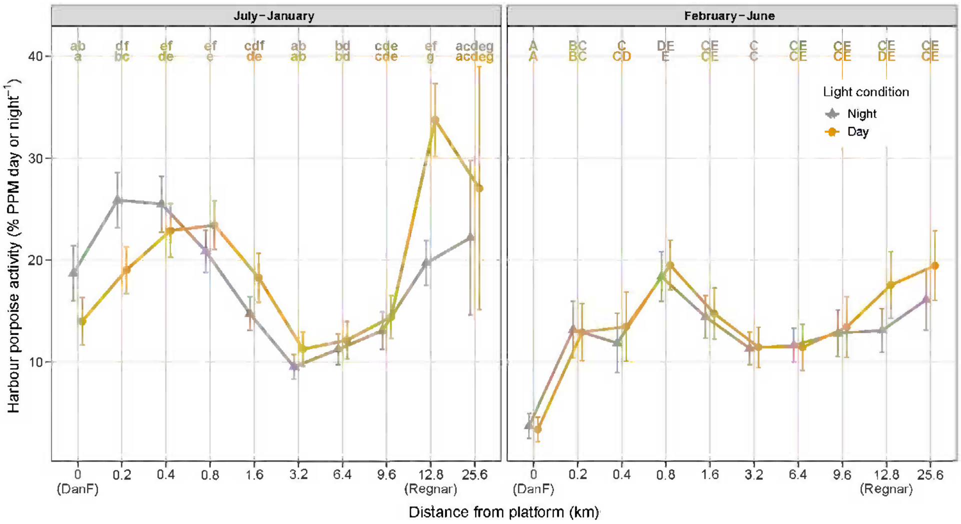

FIGURE 3 Porpoise echolocation activity (porpoise-positive minutes %PPM; mean and 95% CI, pooled for both sampling years and for data from the same distances) recorded during day (yellow) and night (grey) at distances from 0–25.6 km from DanF. Regnar (12.8 km) is a closed submerged wellhead. Letters above each distance show whether %PPM is significantly different between night and day and between distances. Same letter for two distances means no statistical difference between the groups, for example porpoise activity during July-January for 0.4, 0.8, 1.6, 9.6 and 25.6 all have an 'e' at the top of the graph during the day and are therefore not significantly different. The two seasons are not compared in this test. Note that the noise at 0 km is masking up to 50% of the porpoise echolocation compared to 0.2–0.8 km and may explain the low detection rate closest to the platform (Clausen et al., 2018). This effect gradually diminishes out to 12.8 km (see the discussion for more details)

percentage of %PPM was logit transformed to fulfil the assumption of normality of residuals and analysed using linear mixed effects models with the interaction between month and platform (+control) as a fixed effect.

2.3 | Data analysis: Noise

The broadband acoustic data were analysed using custom-written routines in Matlab R2015a (Mathworks, Inc., Natick, MA, USA). For ease of processing, the 46-min-long SM2M+ or SM3M+ sound files were subdivided into sections of 10-s duration that were subsequently averaged over 5 min. Prior to averaging, the routines excluded logger artefacts and porpoise clicks from further analysis (Clausen et al, 2018). Up to ten 10-s-long sections per 46-min file were removed this way.

The mammalian auditory system is typically modelled as a filter bank approximated by one-third octave bands (Richardson et al., 1995). Hence, we calculated the received third-octave rms sound pressure levels (TOLs, dB re 1 μPa rms), using a third-octave filter bank implemented in Matlab according to the ANSI standard S1.6-1984 (Christophe Couvreur, Faculte Polytechnique de Mons, Belgium). Occasionally, very brief noise events exceeded the clip level of the broadband recording device, but given the temporal resolution of the data, this should not have affected the average TOL values.

Our analysis focused on bands with the highest noise levels (centred at 315 Hz, 5.0 and 31.5 kHz), and on a subset of bands highlighted in the EU's Marine Strategy Framework Directive (centred at 63, 125 and 2000 Hz). For each frequency band, we tested for differences in ambient noise levels (mean TOL over 5 min) as a function of distance to the platform, taking into account both D/N conditions and the two porpoise activity periods identified with the GAMMs. To do so, we fitted linear mixed effects models with the three-way interaction between distance to platform, D/N condition and porpoise activity period as a fixed effect.

3 | RESULTS

Over the 2 years of data collection, the 18 C-PODs yielded data from a total of 9917 days, out of a possible 12,417, which gives a recording coverage of 80%. Data from the five broadband noise loggers amounted to a total of 2264 days, out of 3650 days possible, giving a recording coverage of 62% (Table S1 in the Supporting Information).

3.1 | Spatial and diurnal acoustic activity

Porpoise activity varied considerably within the study area (Figure 3). Echolocation activity was about 1.5–2-fold higher close to DanF (≤800 m; mean: 224–291 %PPM/day) and at Regnar (mean: 269 %PPM/day) compared to measurements from stations located between 1.6 and 9.6 km from DanF (mean: 135–196 %PPM/day). Data from 25.6 km were only available for January–June in 1 year, and the porpoise activity was similar to Regnar.

A strong diel pattern in harbour porpoise %PPM and BPM was found within 200 m of DanF and Regnar during July–January. In the vicinity of DanF, %PPM and BPM were 50–70% higher during the night compared to day (Figures 3 and 4), while the pattern was reversed at Regnar.

Porpoise activity data recorded within 200 m of the three additional platforms showed a three- to six-fold increase in %PPM between May

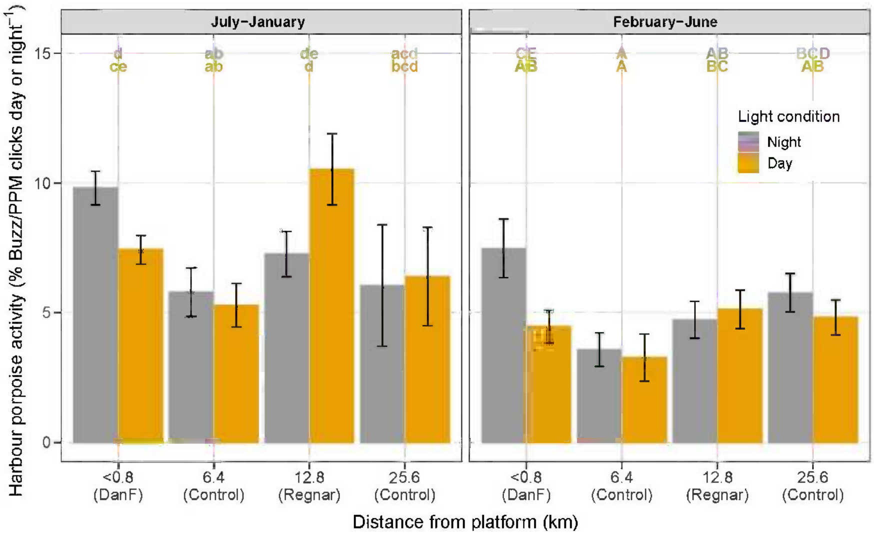

FIGURE 4 Porpoise foraging activity (percentage of buzz-positive minutes, BPM, in relation to %PPM; mean and 95% CI) recorded during day (yellow) and night (grey) at different distances from DanF over the two-year monitoring. Regnar (12.8 km) is a closed submerged wellhead. Letters above each distance show whether %BPM/%PPM is significantly different between night and day and between distances. The same letter for each category means no statistical difference between the groups. Note that the values are not compared between seasons

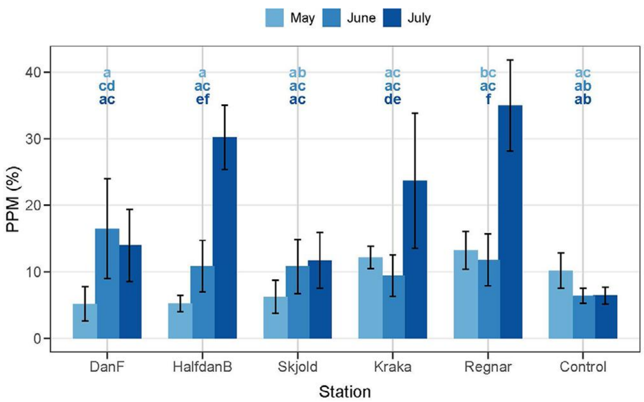

FIGURE 5 Harbour porpoise acoustic activity (%PPM: mean and 95% CI) during May–July 2014 at 200 m from five O&G structures of various sizes (from largest to smallest: DanF, HalfdanB, Skjold, Kraka, Regnar), and at control stations (mean of two stations positioned 6.4 km from DanF. Note that data from the control station at 25.6 km were not available for May–July 2014). Letters above each station show whether %PPM is significantly different between month or platform. The same letter indicates no statistical difference between the groups

and July, confirming the results of the 2-year study at DanF and Regnar (low %PPM February–June and high %PPM July–January; Figure 5).

3.2 | Noise level and distance to platform

Third-octave levels (5 min avarge) for 3 days are shown in Figure 6 to illustrate a quiet, medium- and high-noise day. Noise levels were highest close to DanF and decreased with increasing distance from the platform, showing that the platform was the main contributor to the sound level at 0, 200 and 800 m (Figure 6). There were no clear diel patterns in noise levels. At Regnar (12.8 km), the noise levels were generally low and not clearly linked to platform noise, with most energy at about 200 Hz, characteristic of distant passing ships (Figure 6; Hildebrand, 2009).

The platform noise covered the full bandwidth of the SM2M+ loggers (Figures 7 and S2 [in the Supporting Information]). The highest 5-min TOL were observed immediately under the platform (Figures 7 and 8). TOL reached a maximum of 115 dB re 1 μPa rms in the 315-Hz band, whereas the lowest TOL was on average around 80 dB re 1 μPa rms in the band centred at 80 kHz, while the higher frequencies were limited by the self-noise of the instruments (Figures 7 and S2). Noise levels at Regnar and at 25.6 km were similar within a few decibels across all frequencies, likely representing the background noise level in the central North Sea (Figure 7). Based on the harbour porpoise audiogram, the noise generated from the platform is estimated to be audible to porpoises in the frequency range from 350 Hz to 160 kHz (Figure 7).

In all six third-octave bands examined in Figure 8, mean noise levels gradually decreased with distance from the platform out to Regnar, irrespective of time of day or porpoise activity season (Figure 8). There were no differences in average TOLs between Regnar and the reference stations (25.6 km), except in the 63-Hz band where the reference stations recorded significantly higher noise levels, likely due to their proximity to the shipping lanes between Skagerrak and Southern North Sea (Figure 8).

4 | DISCUSSION

To our knowledge, this is the first comprehensive study on the distribution and foraging activity of harbour porpoises around O&G production platforms. Overall, high porpoise presence and foraging activity were found year-round within 800 m of a large offshore O&G platform in the North Sea, especially at night and during July–January. As such, prediction 1 stating that O&G platforms mainly act as a source of noise disturbance was not supported, as significantly lower porpoise activity was only detected immediately under the platform in the February–June period, but not at other distances or months. Instead, we found supporting evidence for prediction 2 that O&G structures act as a

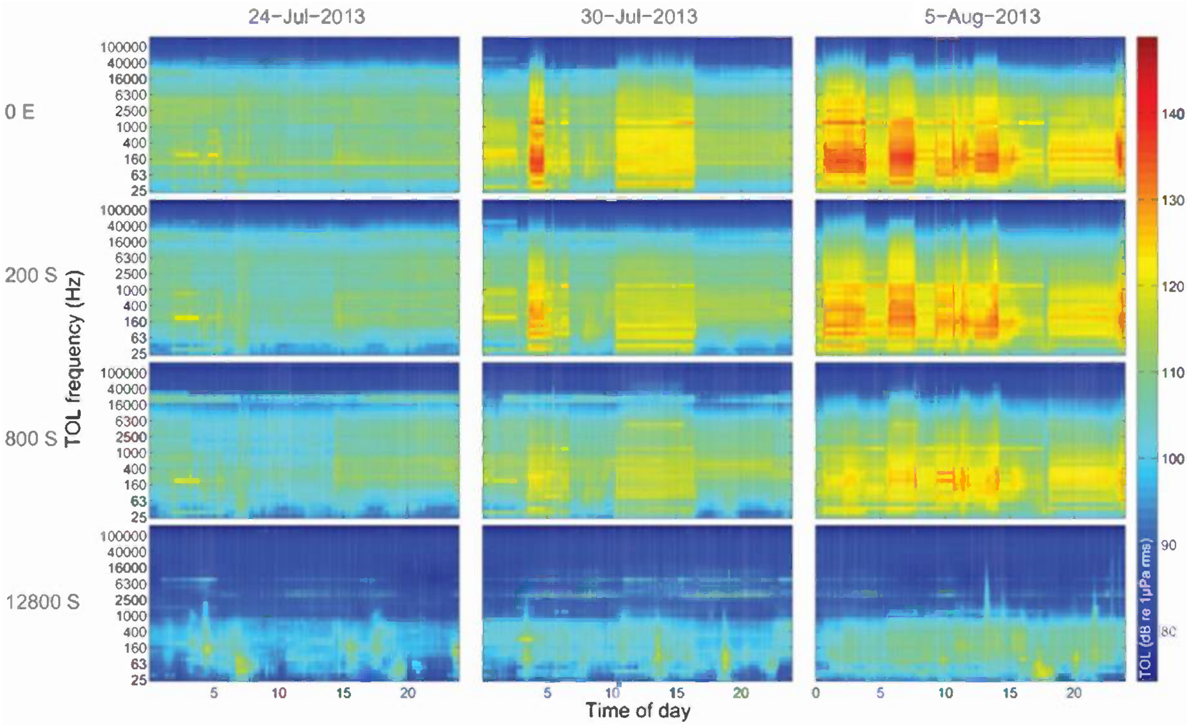

FIGURE 6 Third.octave level (TOL) of noise recorded around DanF, shown for three different days (top) and four distances from the platform (left in m) to illustrate temporal variation in noise. Note that the same noise events recorded close to the platform can be followed with decreasing intensity at further distances

source of attraction, as porpoises were more active in the direct vicinity of the platform compared to the surrounding area, especially from July to January when significantly higher echolocation rates and foraging activity were detected near the platform. A similar pattern was also observed at 200 m from four other O&G structures in the central North Sea, where %PPMs increased during summer compared to the control.

4.1 | Distribution of harbour porpoises around O&G platforms

Our results suggest two distinct activity periods of harbour porpoises around O&G platforms in the North Sea, (1) from July to January, relatively high densities of harbour porpoises were recorded around DanF (up to 800 m) compared to stations located further away, (2) during the remaining 5-months, (February–June), harbour porpoise densities were generally lower and more evenly distributed across the distance gradient except at stations 0 m where porpoises seemed to be avoiding the immediate vicinity of the platform.

We consider the porpoise activity at 25.6 km to represent relatively high density in the general area, as the modelled porpoise density here is somewhat higher than in the oil platform area (Figure 2) and the background noise level is not affected by the platforms (Figure 7). The performance of acoustic detectors, in terms of detection probability, drops with decreasing signal to noise ratio by masking the signals, with the effect that fewer echolocation signals will be recorded in the vicinity of platforms compared to areas with lower ambient noise levels (e.g. Clausen et al., 2018). Therefore, if porpoises were uniformly distributed across our study area, we would expect fewer porpoises to be detected close to the noisy platforms, with increasing detector performance out to the natural background noise level for the North Sea, which seemed to be at 12.8 km, as Regnar and the 25.6 km station had identical background noise levels (Figures 6 and 7). However, our results demonstrate the opposite with highest %PPM values within 800 m of the platform during both periods. Clausen et al. (2018) showed that about 50% fewer minutes with porpoise clicks (PPM) where found when the background noise increased by around 10 dB. As the background noise increased from 0 m to 200–800 m by about 10–12 dB in the frequency range 2–40 kHz (Figures 7 and 8; the noise difference at higher frequencies could not be detected due to the self-noise of the data logger), we could expect that only about half of the %PPMs were detected by the instruments at 0 m compared to 200–800 m. This could easily explain the reduction in detections under the platform and could even suggest that the highest detection levels could be found right under the platform. However, it is not possible to separate the deterrent effect of the noise on the porpoise behaviour and the effect of masking of porpoise echolocation signals.

The theoretical maximum detection range is about 400 m for a C-POD, but in practice due to the directionality of the click emissions and the masking from noise (Clausen et al., 2018; Kyhn et al. 2012), most detections of porpoises will occur at less than 200 m. In light of this detection range of porpoise echolocation, we may consider 800 m to be within the zone that will benefit from the artificial reef and the 500-m fishing exclusion zone. The reef effect may result from the water

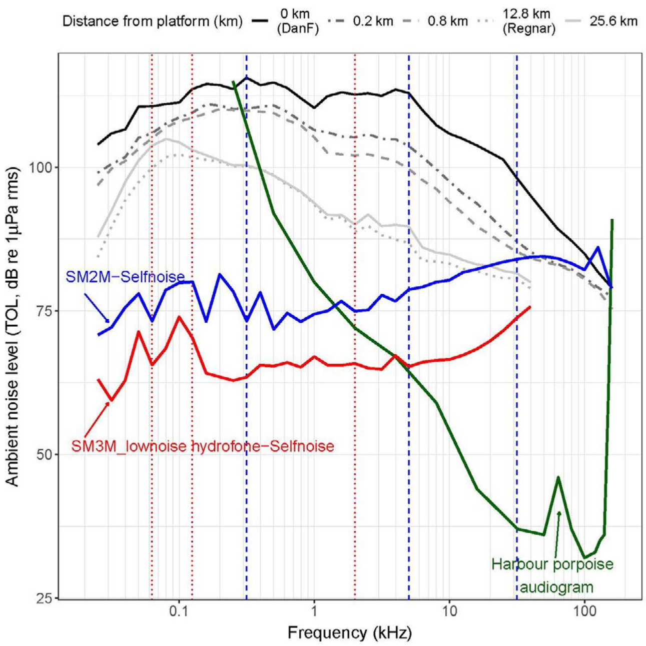

FIGURE 7 Average ambient noise measured as TOLs (5 min average) at five distances (see the Supporting Information for the variation in noise levels). Note the lower sampling frequency for 12.8 and 25.6 km. Centre frequencies of bands within the hearing range of porpoises (315 Hz, 5 and 31 kHz) are indicated with blue dashed lines (see Figure 8). Centre frequencies recommended within the Marine Strategy Framework Directive (63, 125 and 2000 Hz) are shown with red dashed lines (see Figure 8). The blue and red lines show self-noise of the two logger models used in the study, and the green line shows the audiogram of the harbour porpoise (Kastelein et al., 2010)

turbulence around a structure bringing nutrients towards the photic zone, which will increase the productivity around the platform. Also the movement of pelagic fish between structures likely increases fish biomass. Only between February and June, low echolocation activity was observed directly underneath the platform; however, it should be noted that, when porpoises were detected under the platform during this period, they were frequently observed buzzing. Although, false-positive detection rates are positively correlated with background noise, the detector and click-algorithm used in this study were optimized following Clausen et al. (2018), who found relatively low false positive rates, while true positive detections remained high at noise levels similar to those recorded here. We therefore conclude that (a) porpoises are present in high densities around DanF especially during July–January and (b) given the high percentage of feeding buzzes, they go there to forage. Because porpoise acoustic activity at four additional O&G structures, that were all installed decades ago, showed a similar shift from low to high porpoise echolocation activity from May to July, we also conclude that our results are not related to a specific platform of a certain size or sound source level. The five O&G platforms investigated here are representative of O&G platforms operating in the shallow (<50 m) parts of the North Sea and range from a small subsurface closed well through unmanned single-pile platforms to large manned production platforms with regular helicopter and service ship activity.

4.2 | Spatial and temporal distribution of harbour porpoises

The high porpoise activity close to the platform from July to January is broadly consistent with results in Gilles et al. (2016) (Figure 1), who found higher porpoise densities in the central North Sea during summer (June–August) than in spring (Mar–May), with intermediate densities during fall (September–November). The 25.6 km control station seems to have been placed in a slightly higher density area, as this station detected much higher porpoise activity than the control stations closer to DanF. Nonetheless, and considering the lower detection range of the acoustic recorders placed in the noisy environment close to the platforms, we found a similar or higher porpoise activity closer to the platform as well as higher feeding buzz rates.

In the southern North Sea, a study conducted at a Dutch offshore wind farm also showed strong seasonality in porpoise activity within the wind farm, with more echolocation recorded during winter months (Scheidat et al., 2011). In support of our results, they found that acoustic activity was significantly higher inside the wind farm than in control areas, suggesting attraction to the artificial hard-substrate structures and/or to the area where fishery was not allowed and seabed was restored, akin to a marine protected area (Scheidat et al., 2011).

Changes in the sound levels around the platform were consistent throughout the year and thus cannot be directly linked to the seasonal variation in harbour porpoise distribution. The period from July to January matches the period when porpoises increase their food intake to build up a sufficient insulating blubber layer to survive the decreasing water temperatures during winter months (Rojano-Doñate et al., 2018). Mother–calf pairs are often sighted from platforms in the area (Delefosse et al., 2017), and this period also corresponds well with the higher energy demand of porpoise mothers to feed their young calves. The predictable food source close to the platforms may therefore play an important role in supporting the annual energetic strategy of porpoises in the area (Fujii & Jamieson, 2016), and porpoise activity around platforms is likely related to increased foraging opportunities on certain prey species that use O&G structures and the surrounding fishery-free zone as artificial reefs for shelter and/or to find food.

4.3 | Fish distribution around platforms

Several studies in the central North Sea have documented a variety of fish assembling around platforms including Atlantic cod (*Gadus morhua*), pollack (*Pollachius pollachius*), common ling (*Molva molva*), dab (*Limanda limanda*), lumpfish (*Cyclopterus lumpus*), and perhaps most importantly for porpoises, abundant schools of juvenile gadoids (Todd et al., 2018). A long-term study of fish distribution around a platform in the northern North Sea (Miller, UK) also showed high abundance of saithe (*Pollachius virens*), haddock (*Melanogrammus aeglefinus*), and cod (Fujii, 2015). Some seasonal and inter-annual variation in densities of these fish were found, but the changes were relatively minor and are unlikely to fully explain the shifts observed in porpoise presence near

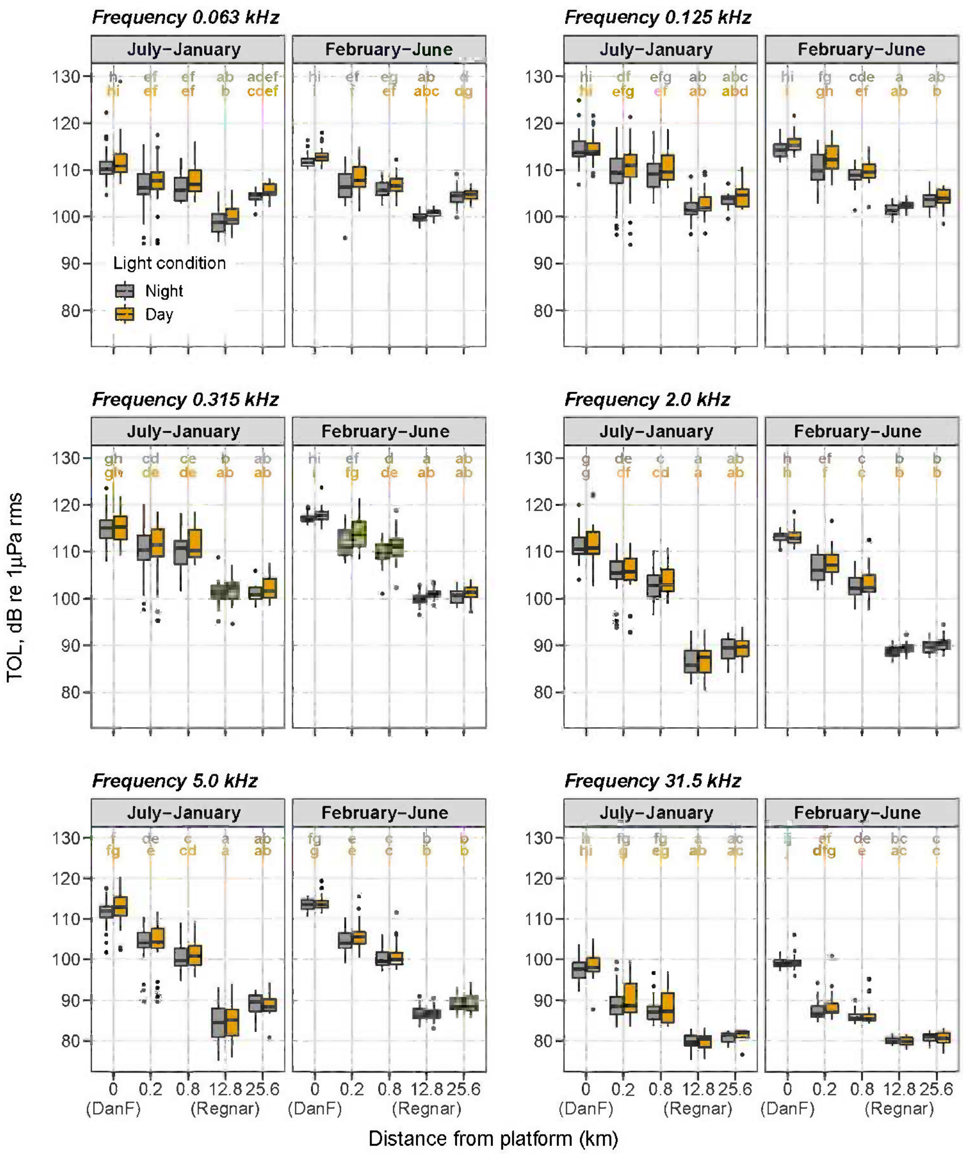

FIGURE 8 Ambient noise measured as 5-min average third-octave-level in bands centred at the six frequencies indicated in Figure 7. Box plots are shown for day (orange) and night (grey) for five distances from DanF. Letters above each distance show whether the noise level is significantly different between seasons, day and night or between distances. The same letter indicates no statistical difference between the groups

DanF in June/July and January/February. However, fish abundance assessments conducted out to 1.4 km from a Norwegian platform in the central North Sea (Albuskjell) using commercial gillnets found saithe and cod to be the most abundant species, with the highest abundance very close to the platform (50–100 m) in May. In September, fish abundance peaked a bit further from the platform at 200–300 m (Løkkeborg et al., 2002). Although the fish caught were larger than typical porpoise prey size (64–73 cm cod), these results indicate the presence of other predators around platforms and suggest that seasonal changes in local prey distribution may be an important factor underlying the variation in porpoise echolocation activity around platforms. Lower porpoise detection rates from February to June immediately under DanF may reflect seasonal migration of fish and a lack of suitable prey for porpoises around the platform during these months. This effect may be strengthened by the higher noise level around platforms.

Besides seasonal patterns, our results revealed a diel variation in harbour porpoise echolocation and foraging activities, with highest click and buzz detection rates during the night close to DanF. This is consistent with other studies conducted around artificial structures in the North Sea (Todd et al., 2009, 2016). However, we found the reverse pattern (low activity – night; high activity – day) at Regnar (Figures 3 and 4), where there is no artificial light, and no difference at Kraka, which is a small unmanned platform (data not shown). On manned offshore platforms, lights are turned on at night and it is possible that artificial light may attract porpoise prey towards the platform. The importance of artificial light to fish communities around offshore platforms was investigated in the Gulf of Mexico (Keenan et al., 2007).

The study suggested that platforms extend the foraging environment of larval, juvenile and adult fishes by providing sufficient light to locate and capture prey, as well as by attracting and concentrating positively phototaxic prey taxa. Similarly, higher fish densities were observed in the water column during night around the Miller platform in the North Sea, although it is unknown how light influenced this pattern (Fujii & Jamieson, 2016). Even though light measurements at night at DanF and at Miller were below the detection limit of the equipment (< 10 lux at 1 m depth; data not shown; Fujii & Jamieson, 2016), some fish species (adult and larvae) are known to be sensitive to light levels about two to three orders of magnitude lower than this level (Keenan et al., 2007). Nonetheless, an investigation of harbour porpoise acoustic activity before-during-after the restoration of a natural stone reef showed a significant increase in porpoise presence, especially at night, compared to the period before the reef was restored (Mikkelsen et al., 2013). Furthermore, higher buzzing rates were generally seen during night in porpoises tagged with acoustic behavioral tags (Wisniewska et al., 2016, 2018). We therefore do not know whether artificial light and flares from the platforms contributed to the increased porpoise feeding activity at night.

4.4 | Noise from the platform

Machinery on O&G platforms is above sea level; however, noise produced by pumps, generators, cranes and other equipment is expected to propagate underwater through vibrations via the platform's metal legs (Genesis Oil & Gas Consultants, 2011). In addition, ships and helicopters servicing platforms, and bubble cavitation from discharge of cooling and produced water could all contribute to higher noise levels. As this study was not designed to identify single sound sources on platforms, the overall sound emissions from DanF were reported instead. Importantly, DanF is close to the main shipping route between the English Channel and north of Denmark, so the generally higher noise levels at 63 Hz is likely driven by heavy ship traffic that dominates this frequency (Richardson et al., 1995). We found that noise generated by DanF was clearly detectable out to at least 800 m from the platform but dropped below background levels at 12.8 km from the source.

The platform produced noise across harbour porpoise hearing range, from 350 Hz to 160 kHz. Although noise levels from the platform at the 16-kHz TOL band may at times exceed noise levels (96 dB) shown to decrease foraging activity and cause avoidance reactions in porpoises (Figures 6 and 7; Wisniewska et al., 2018), we found that porpoises were apparently attracted to the immediate vicinity of the platform during July–January, while for the rest of the year high porpoise presence was recorded 200 m from the platform. In harbour porpoises, behavioural responses to noise generally occur 40–50 dB above the hearing threshold at a given frequency, meaning that any sound above 100 dB re 1 μPa in the frequency range of 10–130 kHz could cause behavioural disturbance (Tougaard et al., 2015). As such, only the average noise levels at 0 m consistently create potential behavioural disturbance, while at distances out to 800 m from the platform, disturbance would be predicted only occasionally (Figure 7). Our results suggest an attraction to the platform, which we interpret to result from the motivation to find food being higher than the potential aversiveness to the noise. It may also be that some porpoises have habituated to the noise coming from a predictable location, primarily the platform or that only more tolerant animals use the habitat around platforms.

4.5 | Remove or leave in situ O&G platforms when decommissioned?

Offshore installations have been shown to act as artificial reefs and important habitats for local ecosystems in the North Sea and elsewhere (Fowler et al., 2020; Macreadie et al., 2011; Todd et al., 2009, 2016, 2018). To illustrate the importance of hard substrate habitats, a questionnaire was circulated among experts in marine science and management. The results revealed that 95% of experts asked argued for the importance of artificial reefs around O&G platforms as habitats worth protecting in otherwise intensively fished areas (Fowler et al., 2018). The need for hard structures on the seabed is further reinforced by the extensive extraction of natural stone reefs for construction of harbours or work on land over the past century. To compensate for this loss, stone reefs are being re-established, where the benefit to harbour porpoises have been documented (Mikkelsen et al., 2013). The value of hard substrate habitats should be seen in the holistic context of historic habitat quality, pros and cons of artificial reefs from offshore installations and the need to re-establish lost hard substrate habitats like stone reefs or oyster beds.

This study confirms that O&G platforms attract harbour porpoises, although the importance of offshore installations on a population-scale remains unknown. However, hard substrate and untouched seabed are rare and serve as valuable habitats to many organisms in heavily trawled waters like the North Sea (Hiddink et al., 2006; Houziaux et al., 2011). Although the OSPAR Commission's Decision 98/3 requires complete removal of offshore installations in the North Sea (www.ospar.org/convention), future O&G platform decommissioning should consider the loss of biodiversity as a consequence of removal of the artificial reef ecosystem. Here the need for scientific evidence is clear to inform policy on decommissioning strategies accounting for both the positive and negative sides of artificial structures.

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AUTHORS' CONTRIBUTION

K.T.C., J.T and M.D. conceived and designed the study; K.T.C. and J.D.B. prepared and programmed the recording instruments; K.T.C., J.T. M.D. and J.D.B. collected the data; K.T.C., D.M.W. and J.D.B. processed and analysed the data; F.M.vB. performed statistical analyses with guidance from J.T and M.D.; J.T. and K.T.C. drafted the manuscript. All authors contributed critically to the drafts and gave final approval for publication. K.T.C. and J.T. made an equal contribution to the paper.

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.msbcc2fw5 (Teilmann, 2021)

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