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Harbour porpoises exhibit localized evasion of a tidal turbine

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Abstract

1. Tidal energy generators have the potential to injure or kill marine animals, including small cetaceans, through collisions with moving turbine parts. Information on the fine scale behaviour of animals close to operational turbines is required to inform regulators of the likely impact of these new technologies.
2. Harbour porpoise movements were monitored in three dimensions around a tidal turbine for 451 days between October 2017 and April 2019 with a 12-channel hydrophone array.
3. Echolocation clicks from 344 porpoise events were localized close to the turbine. The data show that porpoises effectively avoid the turbine rotors, with only a single animal clearly passing through the rotor swept area while the rotors were stationary, and none passing through while rotating.
4. The results indicate that the risk of collisions between the tidal turbine and porpoises is low; this has important implications for the potential effects and the sustainable development of the tidal energy industry.

KEYWORDS
behaviour, coastal, distribution, environmental impact assessment, mammals, renewable energy

1 | INTRODUCTION

Anthropogenic structures in the marine environment are increasing in number with ongoing oil and gas extraction, and the expansion of marine aquaculture and renewable energy (Stojanovic & Farmer, 2013). Renewable energy is a rapidly growing sector on a global scale and electricity generation from tidal stream generators in areas of high tidal flow is increasing rapidly (Ocean Energy Systems, 2019). Cumulative energy produced from global wave and tidal stream sources grew almost 10-fold between 2009 and 2019. Many tidal stream devices resemble small wind turbines mounted on the sea floor, and just as wind turbines pose acute risks to birds (Marques et al., 2014), tidal turbines have the potential to injure or kill marine animals through collisions with moving rotors (Onoufriou et al., 2019). Large animals such as marine mammals are considered to be particularly vulnerable to the risks of collisions (Wilson et al., 2006).

To understand the risks associated with tidal turbines, and to inform the potential impacts associated with the global expansion of the tidal energy industry, information on the movements of animals near operating turbines is required. Unlike terrestrial environments where animal movements or mortalities can be directly observed (Nichols et al., 2018), there are inherent challenges associated with measuring the underwater movements of marine animals, particularly in highly energetic and turbid environments. However, many marine mammal species are highly vocal, using echolocation clicks to actively sense their environment (Au, 1993), and arrays of hydrophones can be used to detect and locate them underwater (Watkins & Schevill, 1972; Macaulay et al., 2017); it is therefore possible to track the movements of these species in the vicinity of tidal turbines (Malinka et al., 2018; Gillespie et al., 2020) and quantify their behaviour in response to the turbines.

This study reports on the effects of a tidal turbine on the behaviour of harbour porpoises (*Phocoena phocoena*) over an 18-month monitoring period. A 12-channel hydrophone system to detect and track the high frequency echolocation clicks of small cetaceans was developed and deployed on an operational turbine off the north coast of Scotland (Gillespie et al., 2020). The fine-scale movements and distribution of individuals that swam within 10s of metres of the turbine were examined along with the effects of turbine blade rotation on their behaviour.

2 | MATERIALS AND METHODS

All procedures and data collection were approved by the University of St Andrews School of Biology Ethics Committee (Reference number SEC18014).

2.1 | Tidal turbines

An array of four, horizontal-axis, 1.5 MW turbines (Meygen, SIMEC Atlantis Energy Ltd) were installed in the Inner Sound, Pentland Firth (58°39′N 3°08′W) off the north coast of Scotland between October 2016 and February 2017 (Figure 1). Two broadly similar turbine designs were deployed; each has three 9-m long blades with a nominal rotation speed of 14 rpm. Each is mounted on a 25 × 19 m three-legged steel turbine support structure (TSS), each leg of which is weighted with 200-t ballast blocks. Turbine hubs are approximately 14 m above the sea floor and 23 m below the sea surface at low tide. A yaw mechanism rotates each turbine so that it always faces the tidal current, which can reach speeds of up to 5 m s^{-1}. The distances between the monitored turbine and the other turbines in the array were between 160 and 300 m. The monitored turbine was installed and became operational in February 2017. Data were collected between October 2017 and October 2019, starting 12 months after the installation of the TSS and 8 months after the commencement of turbine operation. During the study period, turbines were not continuously operational, providing data at all states of tidal flow with the turbine rotating and stationary.

2.2 | Detection and localization

The most south-eastern of the four turbines was instrumented with an array of 12 hydrophones arranged in three tetrahedral clusters mounted on the upper surfaces of the legs of the TSS (Gillespie et al., 2020). Time of arrival differences at the hydrophones within each hydrophone cluster allowed bearings (both horizontal and elevation angles) from that cluster to detected clicks to be calculated; localization in three-dimensions (3D) was possible if a click was detected on at least two clusters. Details of the hydrophone system and its performance are given in Gillespie et al. (2020).

Raw acoustic data (~1 TB per day) were streamed via fibre optic cable to shore and porpoise echolocation clicks were detected in real time using the cetacean acoustic detection software PAMGuard (Gillespie et al., 2008). These detections were then screened offline by a human operator (L.P.) to eliminate false detections, confirm species, and group clicks into events (defined as groups of porpoise clicks separated by 5 min or more). Locations of clicks in 3D were

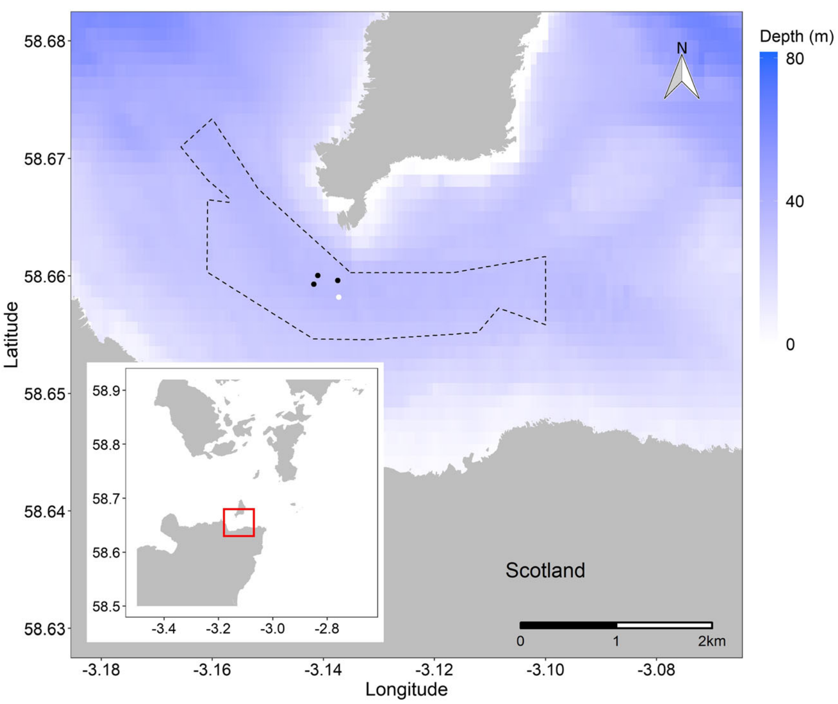

FIGURE 1 Map of the Meygen lease area (dashed polygon) and the locations of the four installed turbines. The monitored turbine is the white point. (Inset) Map of north-east Scotland where the red rectangle shows the area depicted in the main figure

then calculated from the time differences between the same sound arriving on each of the hydrophones. Localization accuracy is generally good (<2 m error) within 10 m of the turbine centre, but becomes relatively poor (several metres error) at distances >35 m. Details of the localization methods are given in Gillespie et al. (2020).

2.3 | Tides, coordinates, and terminology

At the turbine location, the flood tide flows 105°re. N and the ebb tide flows 270°re. N with the turbine rotors facing −75°re. N and +90°re. N for the flood and ebb tides respectively. Tidal flow data were taken from a model provided by SIMEC Atlantis for the turbine location, which has been confirmed through Acoustic Doppler Current Profiler measurements (F. Johnson, SIMEC, personal communication). Localizations were initially calculated in Cartesian coordinates (E = x axis, N = y axis, and height = z axis) relative to the centre of the TSS and the axis of the turbine rotor. The coordinates for localizations during flood tides were then rotated clockwise about the central axis by 165° to put them in the same frame relative to the rotors as the ebb tide localizations. The distance from the centre of the rotors to the centre of the TSS (4.3 m) was then subtracted from all x coordinates; this resulted in transformed x coordinates that are the distance directly upstream of the turbine rotors, y is the horizontal distance in the plane of the rotors, and z is the height above the rotor centre (Figure 2). These transformed coordinates were used in all analyses except for the spatial distribution plots presented in Figure 5.

The 'rotor swept area' or RSA is the 9-m radius circle swept by the turbine blades. While its true position varies with tide direction, in the rotated coordinate system its position is fixed, lying in the y-z plane, with its centre at coordinate (x = 0, y = 0, z = 0). For analytical purposes, the volume around the turbine was divided into five separate regions in the y-z plane, with each region extending ±35 m in x: (i) 'within the rotor swept area' (i.e. a cylinder extending through the rotor swept area); (ii) 'above the RSA'; (iii) 'below the RSA'; (iv) 'to the side of the rotors to a distance of 18 m (twice the rotor radius)'; and (v) 'to the side at distances between 18 and 35 m'. Each click localized within 35 m of the turbine was assigned to one of these regions. Clicks were defined as 'close' to the turbine if they were within two rotor radii in y, at any depth and within ±10 m in the x coordinate (in front of or behind the RSA).

Turbine rotation data (revolutions per minute or rpm) were provided by SIMEC Atlantis at 1-min intervals. There is a small amount of measurement error on the rpm values which tend either to be close to zero (between −0.3 and +0.5 rpm) or above 3.5 rpm with few values between. Here, 'rotating' is defined as a value >1 rpm and 'stationary' as a value ≤1 rpm. The turbine would often rotate for short periods prior to the commencement of power generation. This analysis deals exclusively with rotation rather than power generation.

2.4 | 3D track and click spatial distribution

Click locations within events were viewed manually using the PAMGuard displays and bespoke 2D and 3D displays written in Matlab (Matlab, 2017) and R (R Core Team, 2018). Each event that had one or more clicks localized close to the turbine was examined to see if there was evidence of a track passing through or close to the rotor swept area, and to determine overall movement in relation to the turbine rotors. Each track was classified by two analysts (D.G. and L.P.), as either 'passing' the RSA with a clear swim direction (heading downstream, upstream, crossing in front of or behind the RSA); 'milling', (many clicks close to the RSA with no apparent swim direction), or 'unknown'. The time animals spent in close proximity to the turbine was also examined in relation to tidal flow speed. In the original marking of porpoise events, clicks were put into separate events only if there was a >5-min gap between clicks. Many of these events clearly contained multiple porpoises, or possibly multiple dives of a single porpoise. Marked events were therefore further divided if there was a >20-s gap between clicks. The time from the first to the last click localized as close (i.e. within 10 m up or down stream) to the turbine, within each of these divided events, was then recorded to determine how long individual animals were spending close to the turbine.

The spatial distribution of clicks around the turbine was compared between periods when the turbine was rotating and not rotating to determine whether porpoise distribution was influenced by both the turbine presence and rotation. A series of generalized additive models (GAMs) were used to assess how the number of

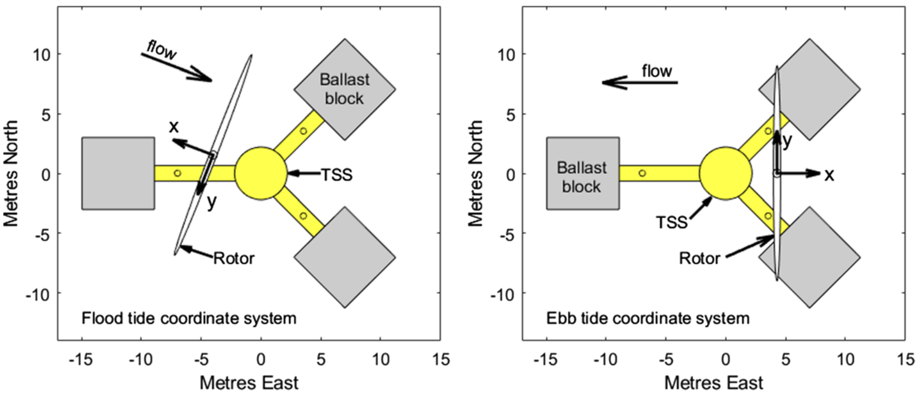

FIGURE 2 Plan view of the coordinate system for Flood and Ebb tides. The turbine support structure (TSS) and ballast blocks are stationary on the sea bed. The rotor is turned to always face the tidal flow. The coordinate systems origin is at the centre of the rotor with the x coordinate pointing directly upstream, the y coordinate across the face of the rotor and the z coordinate vertically upward. Open circles on the legs of the TSS show the positions of the hydrophone system

clicks in each region, measured as a proportion of clicks in all regions, varied with distance up or downstream from the turbine, and between rotating and stationary periods. Thus, if there was no change in the use of the region in response to the turbine, one would expect a constant proportion of clicks at all distances from the turbine. Only clicks within 35 m of the rotors in both x and y were used for analyses due to the poor location accuracy at greater ranges (Gillespie et al., 2020). Each localized click was coded as a 1 or a 0 depending on whether it was located within the respective region. For each region separately, a binomial GAM with logit link was fitted using the function *bam* from the package *mgcv* (Wood, 2017) in R. Explanatory covariates in the model were the distance in front of or behind the turbine rotor and turbine status (i.e. rotating/stationary). For each localized click, the probability that a click at that location would be detected on sufficient hydrophones was estimated using a simulation based on the measured all-around beam pattern of a harbour porpoise (Macaulay et al., 2020) (see Supporting Information S1). The inverse of this probability was then used as a weighting factor of the response variable to account for the varying probability of localization at different points and under different rotation conditions that would otherwise confound spatial patterns in the model output.

The data consisted of observations collected close together in time, resulting in some residual autocorrelation which violates a key assumption of GAMs. Therefore, an AR1 autocorrelation matrix was implemented through *bam* to account for temporal dependence in the model residuals. Localized clicks within the same marked event, were permitted to be autocorrelated. The *rho* parameter controls the degree of permitted autocorrelation (Wood, 2017) and was determined heuristically for each model from autocorrelation function plots by incrementally increasing *rho* from 0.1 to 0.9; a value of 0.4 was selected for the 'to the side of the rotors within 18 m' region and 0.5 was selected for all other regions. Significance of variables was determined using Wald's tests implemented via the *anova.gam* function in the *mgcv* library (Wood, 2017).

3 | RESULTS

Data were collected whenever power was available to the monitoring system; 451 days of continuous data were available from the period between 19 October 2017 and 27 April 2019. Lost days were primarily caused by the turbine being removed for maintenance between 22 September and 19 December 2018. During the data collection period, the turbine was rotating for 282 days (63%) and was stationary for 169 days (37%). A total of 1,414 porpoise events were identified and marked in the data, 525 (37%) of these had no clicks which were simultaneously detected on multiple hydrophone clusters and are assumed to have been porpoises passing at a relatively large distance. A further 545 marked events (38%) had no clicks close to the turbine (two rotor radii to either side and 10 m in front of or behind), leaving a further 344 events (24%) that had one or more clicks close to the turbine. Example tracks close to the turbine are shown in Figure 3. Additional tracks and plotting code are available in Supporting Information S2.

Of the 344 events with clicks close to the turbine, 111 (32%) occurred when the turbine was rotating (>1 rpm) and 233 (68%) when it was stationary (≤1 rpm). Of the events when the turbine was rotating, 11 were judged by both operators to have passed the turbine with a clear swim direction (one above and slightly to the side, 10 below or to the side). A further 19 were judged to be either passing or milling, the remainder being unknown. When not rotating, 27 passed either below or to the side; none were above; one animal clearly passed through the rotor swept area (Figure 3, right). Three further events had clicks localized so close to the rotors that it is possible that they too passed through the swept area (Table 1).

Figure 4 shows the time that animals spent close to the turbine as a function of tidal flow speed. This area extends 10 m upstream and downstream of the turbine rotors; the dashed line in the figure represents the time that a passively drifting animal would take to

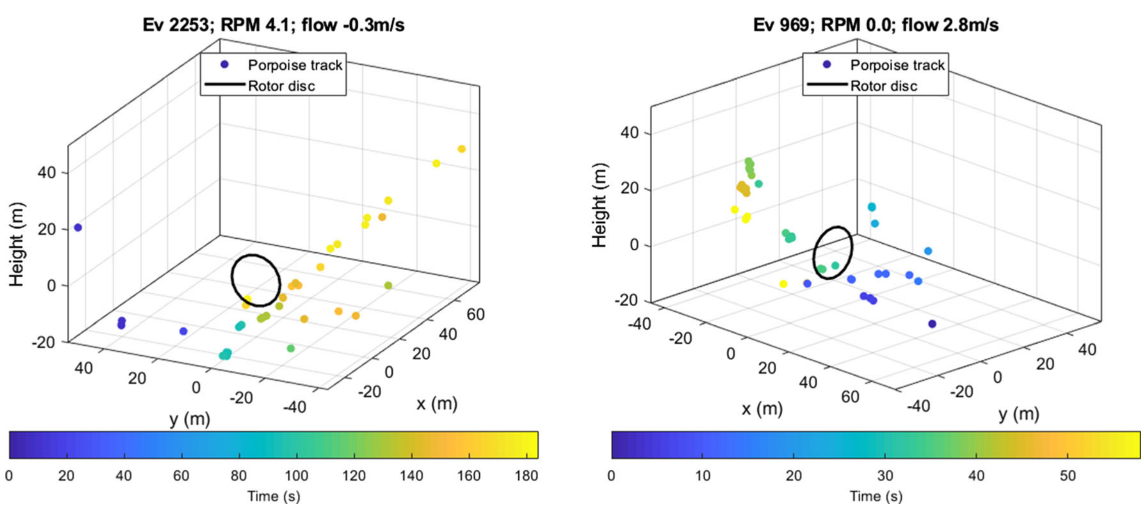

FIGURE 3 Examples of tracks close to the turbine. (Left) A porpoise passing beneath the turbine rotor while it was rotating. (Right) The one porpoise track that appears to pass through the rotor swept area

TABLE 1 Numbers of harbour porpoise passing the turbine or 'milling' around the turbine base

		Turbine stationary (≤1 rpm)	Turbine rotating (>1 rpm)	Total
Passing	Total	31	11	42
	Swim direction	Up = 1; Dn = 25; Cs = 5	Up = 3; Dn = 8	
	Position relative to rotors	BS = 27; R = 1 clear + 3 possible.	BS = 10; A = 1	
Passing or milling		30	19	49
Unknown		172	81	253

Note: Analysts found it difficult to distinguish for many events, so those clearly passing are separate from those for which a clear categorization was not possible. Swim direction: Up = moving upstream; Dn = downstream; Cs = cross stream. Position relative to the rotors: BS = below or to the side; A = above; R = through rotors.

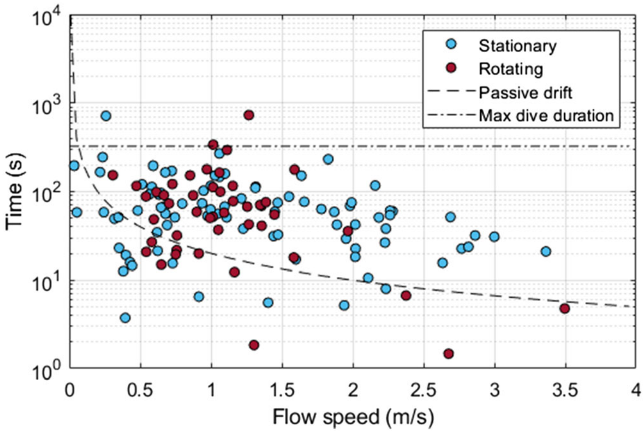

FIGURE 4 Time (note log scale) in close proximity to the turbine for each porpoise event (in this instance a new event being defined as a gap of 20 s or more from the previous click). The horizontal dashed line is at 320 s, which is the longest porpoise dive time reported in Westgate et al. (1995), the curved dashed line is the time an animal passively drifting with the current would take to travel 20 m

travel this 20 m distance based on the respective flow speed. The dotted line at 320 s (5.4 min) represents the maximum dive time for a porpoise given in Westgate et al. (1995). The maximum time spent close to the turbine was 730 s at a flow of 1.2 m s^{-1} and the shortest was 1.4 s at a flow of 2.7 m s^{-1}. One hundred and three out of 133 (79%) divided events (see Section 2.4) spent longer close to the turbine than would be expected if animals were moving passively with the current. It is likely that the longer event durations, particularly those exceeding the maximum recorded porpoise dive time, are caused either by multiple animals or one animal remaining in acoustic range over multiple dives.

The distributions of porpoise click localizations in the vicinity of the turbine are shown in Figures 5–7. Together these figures show that porpoises are distributed all around the turbine. However, porpoises were rarely localized within 10 m directly up or downstream of the rotor swept area irrespective of the operational state of the turbine. The majority of porpoise clicks were localized below the rotors, close to the base of the turbine. There are peaks in the distribution of porpoise below the turbine at +1 m and −10 m from the rotor disk.

Results of the modelling show that the fine scale distribution of porpoises changed with respect to proximity to the turbine; in all regions, the proportion of clicks varied significantly as a function of distance in front of or behind the rotors ($P < 0.0001$; Figure 8). The number of clicks in the rotor swept area decreased with decreasing distance in the x-direction to the turbine, indicating avoidance of the turbine rotors (Figure 8a). There was no significant difference between rotational states of the turbine ($P = 0.0524$), indicating that this pattern of avoidance was consistent regardless of turbine operational status.

The proportion of clicks in the region below the rotor disk (Figure 8b) increased markedly with decreasing distance from the turbine. There were significant differences in the proportion of clicks below the rotors between turbine states in this region ($P < 0.0001$), whereby the proportion of clicks within ±10 m of the rotors was greater when the turbine was not rotating.

There was a very low proportion of clicks above the rotor disk (Figure 8c) and none where they were localized within ±10 m of the turbine in this region. At distances greater than ±10 m, the proportion of clicks above the rotor disk generally increased with increasing distance. There was no significant difference in the proportion of clicks above the rotor swept area between turbine states ($P = 0.834$).

The proportion of clicks to the side of the rotor swept area (within 18 m) varied as a function of distance in front of or behind the turbine, particularly when the turbine was rotating (Figure 8d). When the turbine was not rotating, there was a relatively consistent proportion of clicks as a function of distance in front of or behind the turbine. Turbine rotation had a significant effect on the proportion of clicks in this region ($P < 0.0001$): the proportion of clicks was similar between states upstream of the turbine; however, there was a higher proportion of clicks downstream of the turbine when it was rotating than when it was not.

Further to the side of the rotor disk (18–35 m), there was a marked increase in the proportion of clicks with increasing distance from the turbine rotors (Figure 8e). Overall, there was no significant difference in the proportion of clicks between turbine rotation states ($P = 0.113$); although the proportion of clicks between 10–30 m downstream of the turbine was lower when it was rotating than when it was not. GAM coefficients for all models are provided in Supporting Information S3.

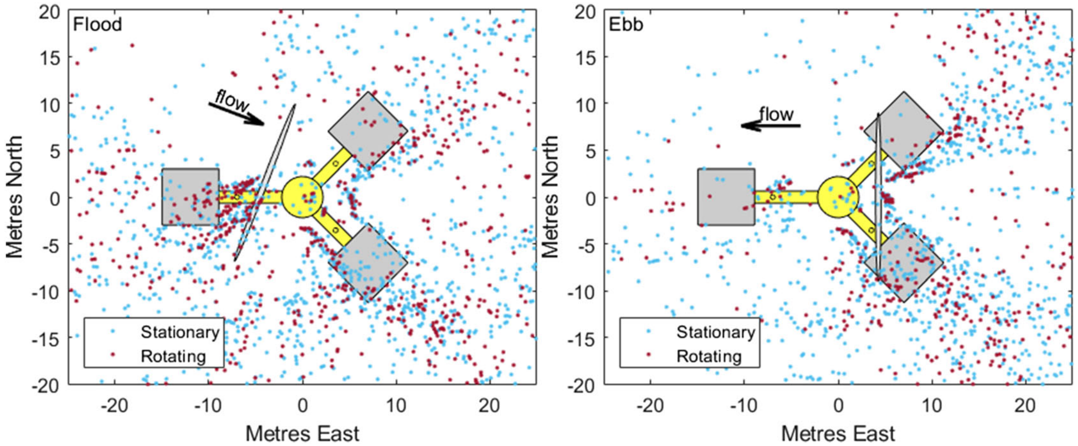

FIGURE 5 Plan view of click locations around the turbine on flood and ebb tides. The metal structure of the turbine support structure is in yellow and the rectangular ballast blocks in grey. The position of the turbine rotors for each tidal state is indicated by the grey oval. Open circles on the legs of the turbine support structure are the locations of the hydrophones

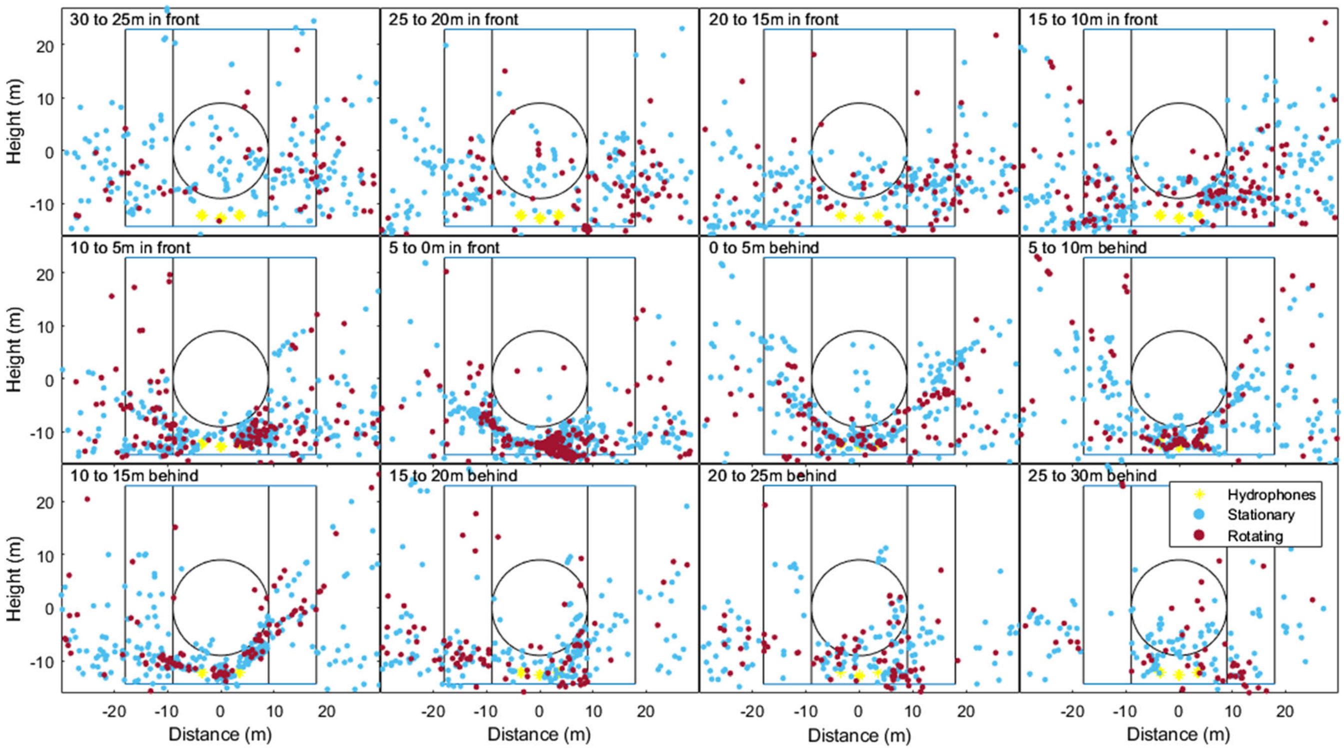

FIGURE 6 Spatial distribution of localized clicks around the turbine during periods of rotation and non-rotation for different distances in front of and behind the turbine. Each panel shows the distribution of clicks around the turbine in a 5-m spatial slice either in front of or behind the rotors. The central circle is the area swept by the turbine rotor, also shown are the regions described above and used in the statistical modelling

4 | DISCUSSION

Acoustic measurements in the vicinity of the turbine (Risch et al., 2020) showed relatively high levels of noise over a wide range of frequencies while the turbine was operating. Low frequency (<1 kHz) sound was 5 dB above measured background levels over 2 km from the turbine and an additional 20 kHz noise was detectable above background levels to at least 200 m. An animal such as the harbour porpoise, which can acoustically sense its environment both passively and actively, would probably be aware of the turbine and its support structure. The acoustic output of the other three turbines in the array has not been measured, although if it is similar to that of the monitored turbine it is likely that porpoises could hear them. While this may affect the overall movement of animals through the area, we

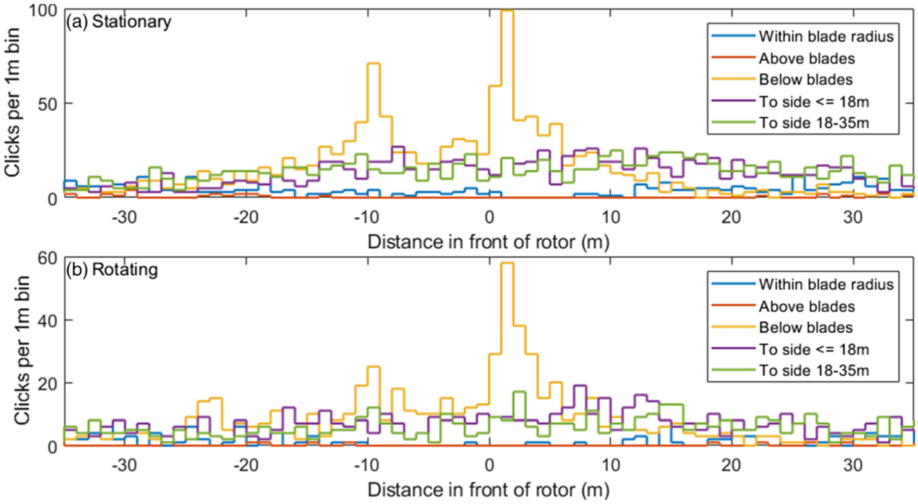

FIGURE 7 Numbers of detections in regions around the turbine plotted against distance in front of (+x) or behind (−x) the turbine for times when the turbine was stationary and when it was rotating. Negative x-axis values indicate behind (downstream of) the rotors

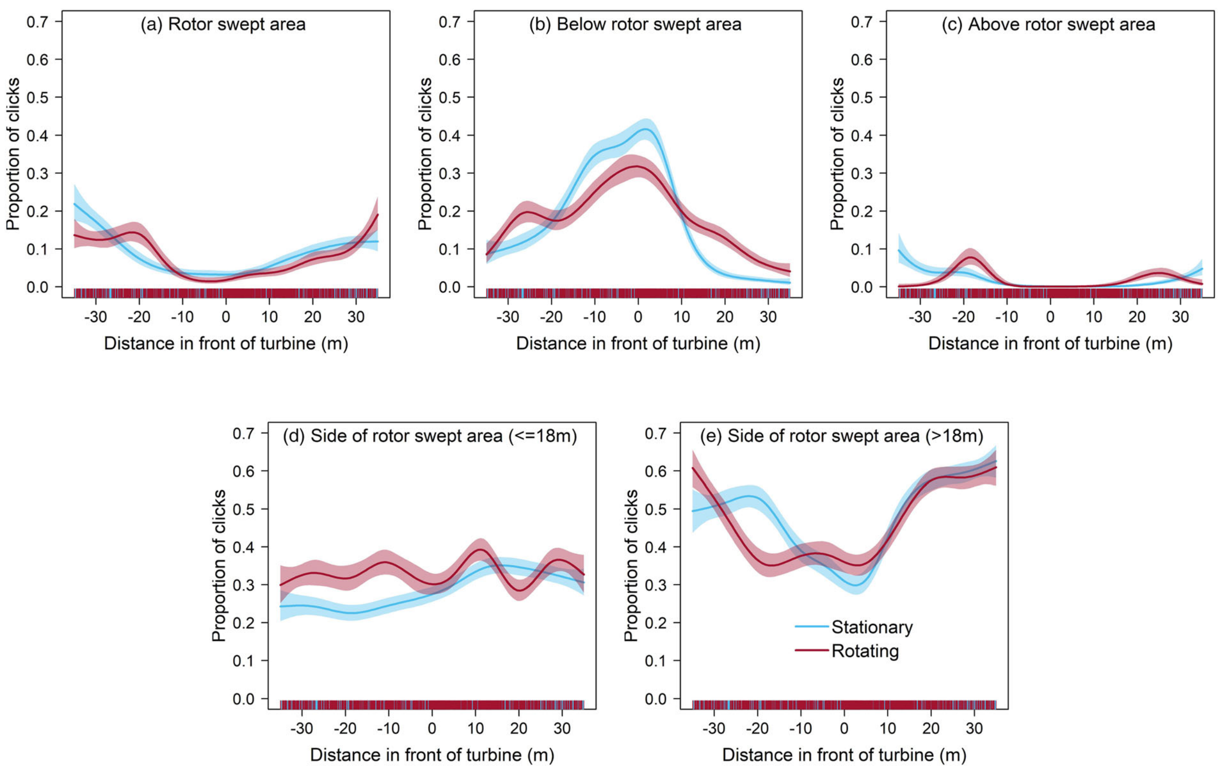

FIGURE 8 Generalized additive model-predicted proportion of clicks in each zone of interest as a function of distance in front of and behind the turbine rotor and turbine operation. Red lines show predictions for times when the turbine is rotating and blue lines when it is stationary. Note the volume of each zone is not equal and therefore absolute proportions should not be compared between graphs/models

believe that the fine-scale distributional changes reported here are most likely to be a response to the one monitored turbine.

The results show that harbour porpoises frequently swam in close proximity to a rotating tidal turbine, but that, importantly, they generally avoided the area close to the rotors whether the turbine was rotating or not. During 451 days of data collection, on 344 occasions, porpoises swam close to the turbine (within two rotor radii to either side and within 10 m upstream or downstream). During periods when the turbine was stationary, a single porpoise track passed through the rotor swept area and three porpoises swam close to the rotor swept area and may have passed through it. When the turbine was rotating, no porpoises clearly passed through the rotor swept area but at least 11 porpoises passed above, below, or to the side of the rotors (Table 1 and Supporting Information S2). The majority of porpoises (75%) appear to have passed the turbine at distances greater than 35 m where accurate 3D localization was not possible. When corrected for localization probability, and autocorrelation between clicks within events, results of the modelling confirmed that there is a significant reduction in the number of localized clicks within 10 m in front of or behind of the rotor swept area compared to greater distances, further indicating localized avoidance of this area.

From the perspective of potential impacts of the tidal energy industry on marine mammals, these results are extremely important. Tidal turbines have the potential to cause injury or mortality to marine mammals through direct contact with moving turbine parts (Onoufriou et al., 2019). However, such impacts would be effectively reduced if animals exhibited appropriate avoidance responses to the turbines. Responses to the tidal turbine occur at two different scales: a separate study showed that there is a significant reduction in porpoise presence within 140 m of the turbine when it is operating (L. Palmer, personal communication); the current study shows that those individuals that do still come close respond to the turbine and directly evade the turbine rotors. This means that the risk of collisions between porpoises and the rotors of the tidal turbine in the current study is likely to be extremely low compared to if the animals were not responding to the turbine.

In contrast to the rotor swept area, a relatively high proportion of clicks were localized below the rotor swept area close to the turbine base; clicks were detected immediately below and in front of the turbine rotor (Figures 4–6) as well as behind the turbine support structure. Further, the proportion of clicks below the turbine increased close to the turbine. This suggests that porpoises are generally moving below the rotor swept area, potentially to avoid the moving rotors. This has important implications for the design of future turbines or the placement of turbines relative to each other in arrays. Specifically, if the area below the rotors is important from an avoidance perspective, it may be pertinent to maintain a suitable distance between the rotor tips and the sea bed in the design of future turbines.

The relative increases in the use of the area below the rotors are also interesting from a biological perspective. The relatively high use of the area around the turbine base may be indicative of the area being important for foraging. For example, evidence shows that anthropogenic structures in the marine environment may act as artificial reefs, which can support diverse communities of marine biota (Rouse et al., 2019). This may underlie recent results showing that some marine mammals appear to forage intensively at individual anthropogenic structures (Russell et al., 2014) and it is conceivable that the turbine support structure in the current study provides a preferential foraging location for porpoises. In support of this, a study of fish behaviour conducted around the same TSS installed in a channel in the Orkney Islands (Williamson et al., 2019) showed that there were significantly more fish schools per hour and a higher fish school cross-sectional area per hour around the TSS compared to a reference site with similar environmental conditions.

The data showing that event durations were considerably longer than expected based on assumed passive drift time from 10 m in front of to 10 m behind the rotors indicate that porpoises are not generally swimming in a directed fashion past the turbine but are actively spending time close to the turbine. Given that tidal flows are frequently far greater than the sustained swimming speed of porpoises $\sim$1.7 m s^{-1} (Otani et al., 2001), this suggests that porpoises are either actively swimming against the current, or are making use of fine-scale hydrodynamic variations to remain close to the turbine. Potential mechanisms for this have been documented in many river dwelling fish species and include flow refuging (where the animal exploits regions of reduced flow as a result of hard structures) or vortex capturing (harnessing the energy of environmental vortices or eddies) (Liao, 2007). This is consistent with the 49 porpoise events that were close to the turbine but did not have a clear track and were judged to be 'passing or milling'. Nevertheless, it is important to consider that, particularly for some of the longer times spent close to the turbine, there may be more than one porpoise present, thereby extending the period for which clicks were being detected. Conversely, shorter times are indicative of porpoises swimming with the current may be due, in part, to a cessation of vocalizations or that calls were not detected.

From a technical perspective, the methods used here appeared robust for tracking porpoises past the turbine. Nevertheless, it is important to consider the potential caveats associated with them. The narrow click beam pattern of porpoise clicks (Au et al., 1999; Macaulay et al., 2020) combined with elevated noise levels during periods of high flow (Gillespie et al., 2020) mean that the probability of being able to detect a porpoise click on sufficient hydrophones for localization was relatively low (although the probability of localizing at least some clicks as an animal passed was of course much higher than the single click localization probability). It is therefore not possible to be certain that no porpoises swam through the rotor while it was rotating during the monitoring period. There is also the possibility that animals may change their acoustic behaviour close to the turbine; for example, reductions in click rates have been observed in tagged harbour porpoise in response to loud vessel noise (Wisniewska et al., 2018). Conversely, they may echolocate more to investigate an unusual structure in their environment. Further, if animals take evasive action and orientate themselves away from the turbine, they are less likely to be detected than if heading towards the turbine. Future studies could combine passive acoustic monitoring with multi-beam active sonars, which could detect and localize silent animals (Hastie et al., 2019), and provide a more consistent detection probability around the turbine independent of location and click behaviour.

The monitored turbine became operational 8 months prior to the start of monitoring. It is therefore possible that the behaviour patterns observed represent conditioned behavioural responses to the rotating turbine, and that responses to a recently installed turbine may be different. Since individual porpoises cannot be identified from passive acoustic data, it is not possible to determine whether these observations represent specialist behaviour by a small number of individuals repeatedly using the area, naïve porpoises encountering the turbine, or a combination of these two.

In this study, data were analysed for a single species close to a single turbine and the results may not be directly applicable to other species, habitats, and turbine designs. Three other turbines in the array were operational for most of the study period, but the other turbines were between 160 and 300 m from the monitoring system, which only provided accurate tracking out to around 35 m. Future commercial scale arrays may contains several tens, or even hundreds, of turbines, which could impact marine life in a number of ways: firstly, the combined acoustic output of many turbines may create a soundscape that acts as a perceptual barrier to exclude animals from the entire array; secondly, the distances between individual turbines in a large array may be smaller, potentially making fine scale evasive behaviour more difficult for individual animals. There is also a possibility that enhanced foraging opportunities may be created by large arrays of turbines, due to fish aggregation around structures, leading to an increased abundance of marine predators. However, future turbines may also be mounted on drilled monopiles or pinned structures rather than the large gravity mount TSS present in this study. If animals are using areas of low flow created by the presence of the TSS, either as a flow refuge or for enhanced foraging, then this behaviour may not occur with a substantially different physical structure. It would therefore be unwise to extrapolate from our data in order to directly predict the likely effect of future turbine arrays.

Despite these caveats, the results presented here show that porpoises were clearly able to detect the presence of the turbine and its support structure and, although there is evidence of some attraction to the turbine support structure, they generally avoided the high-risk rotor region. This information is critical in understanding the environmental effects of these novel, and potentially dangerous, anthropogenic structures. As the tidal energy industry looks to expand, it will also become increasingly important to consider the potential effects of arrays of tens or hundreds of turbines on a range of different wildlife species.

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AUTHOR CONTRIBUTIONS

D.G., G.H., and C.S. developed the overall project. Algorithms and software were developed by D.G. and J.M. Data management and processing was conducted by L.P. and D.G. All authors contributed to drafts of this manuscript.

CONFLICT OF INTERESTS

All authors declare that they have no completing interests.

SOFTWARE AND DATA AVAILABILITY

The PAMGuard data analysis software is open source and available at https://sourceforge.net/p/pamguard/svn/HEAD/tree/PamguardJava/. Simulation software for estimating localisation probability of porpoise clicks is at https://github.com/macster110/cetacean_sim.

The research data supporting this publication can be accessed at https://doi.org/10.17630/c3daebc2-0dfb-4702-941a-3a4e038951de (Gillespie et al., 2021).

OPEN RESEARCH BADGES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at https://doi.org/10.17630/c3daebc2-0dfb-4702-941a-3a4e038951de.

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