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RESEARCH ARTICLE

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# Harbour seals avoid tidal turbine noise: Implications for collision risk

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## Abstract

1. Tidal stream energy converters (turbines) are currently being installed in tidally energetic coastal sites. However, there is currently a high level of uncertainty surrounding the potential environmental impacts on marine mammals. This is a key consenting risk to commercial introduction of tidal energy technology. Concerns derive primarily from the potential for injury to marine mammals through collisions with moving components of turbines. To understand the nature of this risk, information on how animals respond to tidal turbines is urgently required.
2. We measured the behaviour of harbour seals in response to acoustic playbacks of simulated tidal turbine sound within a narrow coastal channel subject to strong, tidally induced currents. This was carried out using data from animal-borne GPS tags and shore-based observations, which were analysed to quantify behavioural responses to the turbine sound.
3. Results showed that the playback state (silent control or turbine signal) was not a significant predictor of the overall number of seals sighted within the channel.
4. However, there was a localised impact of the turbine signal; tagged harbour seals exhibited significant spatial avoidance of the sound which resulted in a reduction in the usage by seals of between 11% and 41% at the playback location. The significant decline in usage extended to 500 m from the playback location at which usage decreased by between 1% and 9% during playback.
5. *Synthesis and applications*. This study provides important information for policy makers looking to assess the potential impacts of tidal turbines and advise on development of the tidal energy industry. Results showing that seals avoid tidal turbine sound suggest that a proportion of seals encountering tidal turbines will exhibit behavioural responses resulting in avoidance of physical injury; in practice, the empirical changes in usage can be used directly as avoidance rates when using collision risk models to predict the effects of tidal turbines on seals. There is now a clear need to measure how marine mammals behave in response to actual operating tidal turbines in the long term to learn whether marine mammals and tidal turbines can coexist safely at the scales currently envisaged for the industry.

**KEYWORDS**
avoidance, behavioural responses, collision risk, marine mammals, marine spatial planning, pinnipeds, renewable energy, seals, tidal turbines, underwater noise

## 1 | INTRODUCTION

Many countries have set ambitious targets for renewable energy, with energy from offshore sources anticipated to form an important part of this; this has led to the proposed installation of tidal stream energy converters (tidal turbines) in many tidally energetic coastal sites. For example, it is estimated that one-fifth of the UK's electrical supply could ultimately come from marine (wave and tidal stream) sources (Callaghan, 2010). Tidal energy extraction is typically carried out using subsurface turbines that extract energy from tidally driven moving water. Although there are a wide range of different designs of tidal turbines, the majority have moving horizontal axis rotors that operate in a similar fashion to wind turbines.

Currently, there is a high level of uncertainty surrounding the nature and extent of any environmental impacts of tidal turbines on marine species (marine mammals in particular) (Inger et al., 2009). However, there is evidence to suggest that marine mammals are attracted to tidally energetic sites (Benjamins et al., 2015; Hastie et al., 2016; Zamon, 2001) and the likely co-occurrence between these species and tidal turbines has led to concerns about potential environmental impacts. Concerns derive primarily from the potential for physical injury through direct contact with moving structures or parts of the devices (Wilson, Batty, Daunt, & Carter, 2007). Other potential impacts include the exclusion of marine mammals from suitable habitats by presenting physical or perceptual (as a result of acoustic emissions) barriers to movement.

Faced with uncertainty about the risks of interactions between tidal turbines and marine mammals, a common approach is to carry out collision risk modelling (Scottish Natural Heritage, 2016; Wilson et al., 2007). This is an approach that has been adapted from methods used to predict the impacts of wind turbines on birds and quantify collision risk based on the structure and operation of turbines, and bird characteristics including flight and avoidance behaviour (Band, Madders, & Whitfield, 2007; Chamberlain, Rehfisch, Fox, Desholm, & Anthony, 2006).

Collision risk for marine mammals depends on the natural densities of animals at the tidal sites and their dive behaviour, which in combination might be considered as providing a three-dimensional prediction of the likelihood of encounter in the absence of any avoidance. This likelihood can then be modified using information on avoidance at two different scales. At a medium scale, of hundreds of metres, animals might avoid the turbine site leading to a reduction in the rate of close encounters. At a finer scale, of metres, individuals might respond directly to evade collision with specific parts of a turbine (e.g. the rotor blades). At present, however, there are no empirical data on whether marine mammals exhibit appropriate responsive movements at either of these scales to reduce the potential for collisions with tidal turbines. This data gap severely limits the effective prediction of impacts on marine mammals which has the potential to curtail acceptance of new proposals, and can create barriers to commercial introduction of tidal energy technology (Hastie et al., 2014).

The paucity of data on behaviour around turbines is primarily due to the very limited number of tidal turbines currently operating world-wide. To circumvent this, it is possible to simulate the likely detection cues for animals and measure responses to these. As most marine mammals have highly sensitive underwater hearing (Richardson, Greene, Malme, & Thomson, 1995), it seems likely that sound produced by operating turbines would provide the most likely means for marine mammals to detect and locate turbines. Therefore, in this study, we investigate the behaviour of a marine mammal species in the presence of a simulated tidal turbine. Specifically, we measure the spatial and temporal patterns of distribution exhibited by harbour seals (*Phoca vitulina*) in response to acoustic playbacks of tidal turbine sounds within a narrow coastal channel of interest to the renewables sector and subject to strong, tidally induced, water currents. This is carried out using data from animal-borne telemetry devices and shore-based observations, to which we apply a series of spatial analyses to quantify behavioural responses to the turbine sounds.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area

The behaviours of harbour seals were studied in a narrow, tidally energetic channel on the west coast of Scotland (Kyle Rhea: 57°14′8.10″N, 5°39′15.25″W). The channel runs from north to south, is *c.* 4 km long and 450 m wide (Figure 1). Water depths within the channel are generally less than 30 m and tidal currents can reach over 4 m/s (Wilson, Benjamins, & Elliott, 2013). There has been interest in developing part of the channel for renewable energy; proposals have included plans for an array of four tidal turbines with an 8 MW capacity (https://tethys.pnnl.gov/annex-iv-sites/kyle-rhea-tidal-stream-array-project). During summer months (April–September), over 100 harbour seals haul out on intertidal rocks along the sides of the channel (Figure 1) and forage within the channel (Hastie et al., 2016).

### 2.2 | Telemetry

To measure the at-sea movements of harbour seals, we deployed animal-borne tags on 10 seals (Table 1) between April and August 2013. Seals were captured while hauled out on, or in the water adjacent to, intertidal rocks using hand or seine nets and anaesthetised with a mass specific i.v. dose of Zoletil® in combination with Hypnovel®.

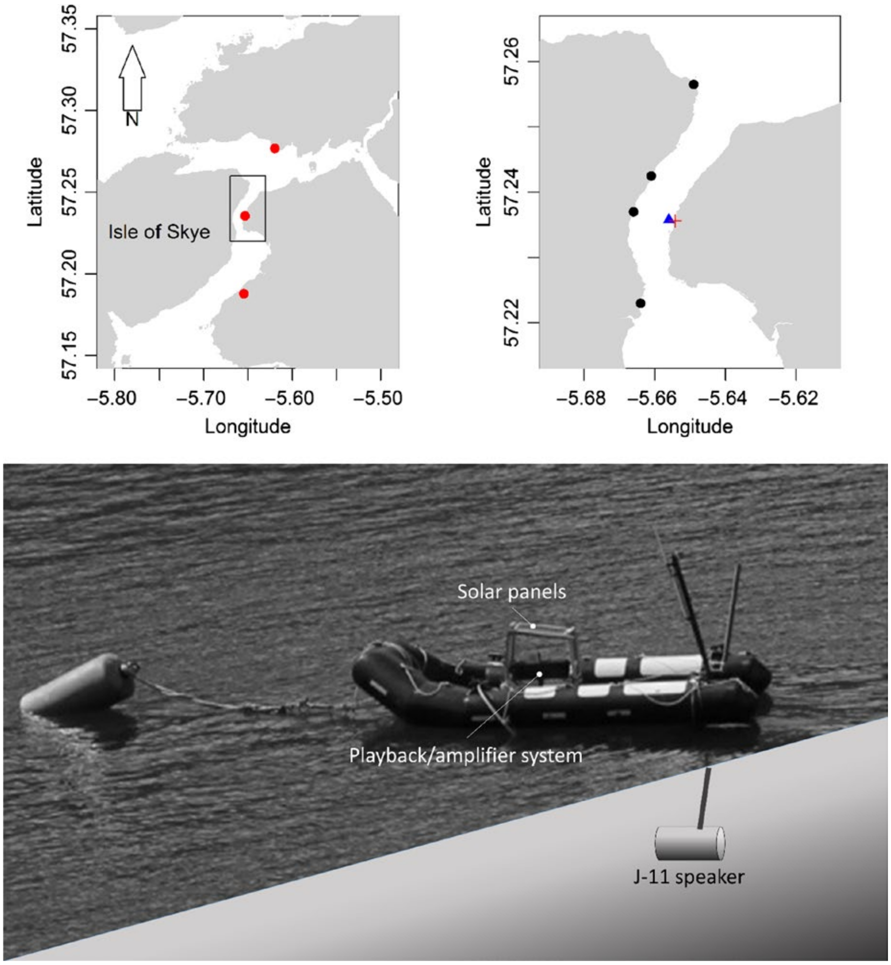


**FIGURE 1** The upper left panel shows a map of the location of study area in the tidal channel (rectangle) and the seal tag receiving stations (points), and the upper right panel shows the tidal channel study area with the locations of the visual observer site (+), the playback boat (triangle) and seal haul outs (points). The lower panel shows the moored playback boat showing the location of the J11 underwater speaker, the playback system, and the solar panels [Colour figure can be viewed at wileyonlinelibrary.com]

Capture and handling procedures are described in detail by Sharples, Moss, Patterson, and Hammond (2012). The tags were attached to the fur at the back of the neck using Loctite® 422 Instant Adhesive. All procedures were carried out under Home Office Animals (Scientific Procedures) Act licence number 60/4009.

We deployed GPS/UHF tags (PathTrack Ltd, Otley, UK) on each of the seals; these are small (370 g: *c*. 0.5% of the average seal mass in this study) data loggers that attempt to record the location of a seal every time it surfaces (approximately every 5 min). The tags recorded GPS data, processed on board using the Fastloc algorithm (Hazel, 2009), allowing locations to be obtained at each surfacing. All GPS data were stored on the tag until they were downloaded by UHF to onshore data-archiving base stations when seals hauled out for a period of at least 30 min within the range of a station (*c*. 16 km).

| Tag ID | Sex | Mass (kg) | Length (cm) | Girth (cm) | Age (years) | Tag duration (days) |
|---|---|---|---|---|---|---|
| 65154 | Female | 82.6 | 138 | 102 | 6 | 75 |
| 65155 | Female | 76.2 | 140 | 102 | 5 | 67 |
| 65156 | Male | 81.6 | 154 | 106 | 6 | 54 |
| 65157 | Male | 89.4 | 151 | 112 | 6 | 96 |
| 65159 | Male | 80.2 | 143 | 112 | 8 | 98 |
| 65161 | Female | 86.4 | 140 | 108 | 9 | 59 |
| 65162 | Male | 68.2 | 143 | 99 | 6 | 67 |
| 65163 | Male | 87.2 | 160 | 106 | 12 | 82 |
| 65164 | Female | 76.0 | — | 93 | 4 | 80 |
| 65165 | Female | 78.4 | 141 | 107 | 13 | 40 |

**TABLE 1** Summary of the tagged seals in the study including the sex, mass (kg), length (cm), girth (cm), age (years: established via tooth ageing Dietz, Heide-Jorgensen, Härkönen, Teilmann, & Valentin, 1991) and the tag deployment duration (days). All tags were deployed in April 2013

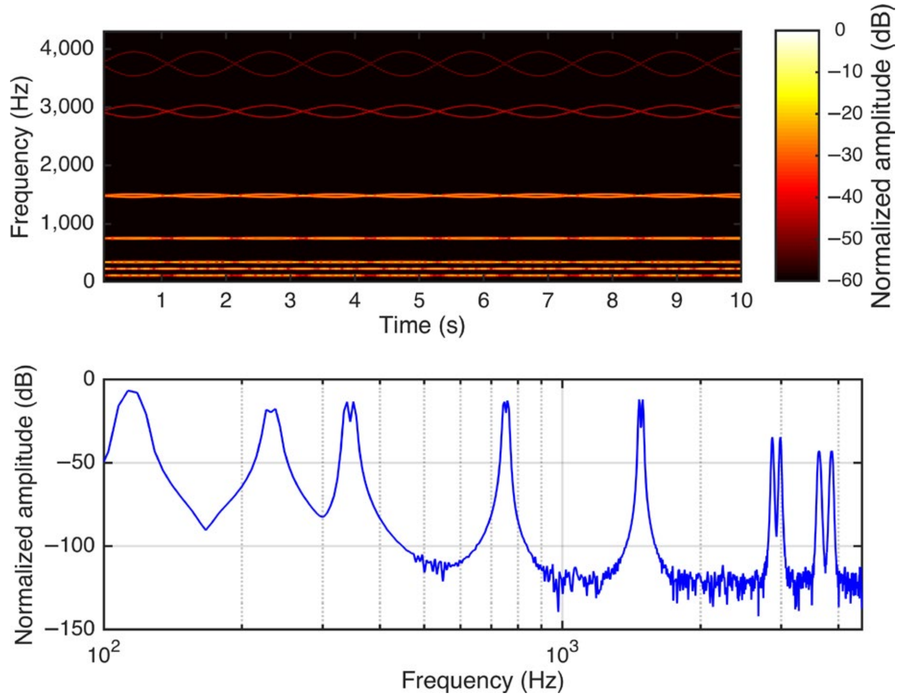


**FIGURE 2** The upper panel shows the spectral output evolution for the simulated tidal turbine signal over a 10 s period (fast fourier transform [FFT] length 4,096, 50% overlap, $\Delta f$ = 10.76 Hz, sample rate of 44,100 Hz). The lower panel is a "snap shot" FFT part way through the 2.1 s frequency modulation cycle (FFT length 8,192, $\Delta f$ = 5.38 Hz, sample rate of 44,100 Hz). The amplitude of each tonal component is normalised to the equivalent broadband source level. The amplitude ratio here is compensated for the relative transmit sensitivity of the transmitter transducer representing the relative ratios the levels in the water [Colour figure can be viewed at wileyonlinelibrary.com]

Three base stations were placed at vantage points overlooking nearby haul out sites (Figure 1). Data were subsequently downloaded from the base stations periodically either by connecting them to a laptop via USB or by wireless transfer through a handheld wireless receiver. GPS data were cleaned and erroneous locations removed using predetermined thresholds of residual error and number of satellites; tests on land using these thresholds showed 95% of the cleaned locations had an error of <50 m (Russell et al., 2015).

## 2.3 | Acoustic playbacks

To measure the effects of tidal turbine noise on the behaviour of seals, a series of acoustic playbacks were carried out. A playback system was deployed on a moored boat 100 m from shore within the channel in a water depth of *c.* 10 m (Figure 1). Signals were played from a laptop computer with a USB audio interface (Creative E-MU Tracker; EMU Systems, Scotts Valley, CA, USA) using a 1,000 W power amplifier (Kenwood KAC7204; London, UK) through an underwater speaker. The speaker (J11 projector; Naval Undersea Warfare Center Division, Newport Underwater Sound Reference Division, RI, USA) was mounted on a pole and deployed *c.* 1 m below the transom of the boat. Full calibration of the playback system (data generation system and transducer) was carried out at the National Physical Laboratories, Wraysbury facility in 2015 allowing accurate estimation of the source levels and signal directionality achieved during the playbacks.

The acoustic signal used was a simulated tidal turbine (Figure 2; described in the Supporting Information). This was based on recordings of a 1.2 MW tidal energy convertor (SeaGen) installed by Marine Current Turbines Ltd in the narrow entrance to Strangford Lough, Northern Ireland (54.3574°N, 5.5412°W) (Robinson & Lepper, 2013).

**TABLE 2** Characteristics of the playback signal based on observed signals from the SeaGen tidal turbine

| Frequency (Hz) | Frequency modulation (Hz) | Source level (dB re 1 μPa-m$_{(RMS)}$) |
|---|---|---|
| 115 | 8 | 169.2 |
| 232 | ±6 | 168.4 |
| 344 | ±17 | 167.2 |
| 753 | ±24 | 167.5 |
| 1,483 | ±47 | 168.3 |
| 2,929 | ±218 | 148.8 |
| 3,746 | ±436 | 143.6 |

The broadband RMS source level of the playbacks was 175 dB re 1 μPa-m$_{(RMS)}$ (Table 2), which was designed to reflect the estimated RMS source level of the real turbine (174 dB re 1 μPa-m$_{(RMS)}$) (Robinson & Lepper, 2013).

Each acoustic playback consisted of a 12-hr period within which 6 hr of turbine signal and 6 hr of no sound were played. A series of 12-hr audio files were created, each with six 1-hr signal periods randomised within them. The playback system was controlled via Wi-Fi from a laptop on shore; each day, a 12-hr audio file was randomly selected for playback. A total of 25 playbacks were carried out between 20 June and 26 July 2013 (Figure S1); playback start times varied between 06.00 and 18.40 hr and were random with respect to stage of tide.

The broadband RMS received level (RL) at each seal location within the channel was estimated using a series of range dependent Energy Flux acoustic transmission loss models (Weston, 1971). These took account of bathymetry (Crown Copyright/SeaZone

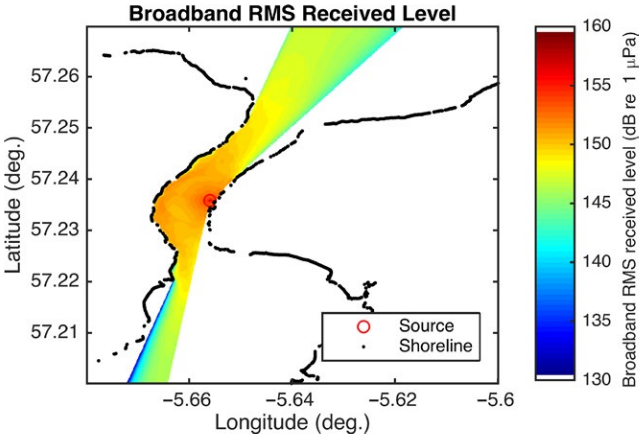


**FIGURE 3** An example of the spatial variation in the modelled broadband received levels (dB re 1 μ$Pa_{(RMS)}$) across the study area during periods with wind speeds of 0 m/s and a tidal height of 0 m above chart datum

Solutions. All Rights Reserved. 052006.001, 31 July 2011) and assumed a stony seabed with sediment sound velocity of 1,788 m/s and density of 2,000 kg/m$^3$. The water sound velocity was assumed to be 1,490 m/s. In addition, the effects of variation in tide height (0–6 m: POLTIPS; version 3.4.0.3/10), wind speed (0–7 m/s: using the visual observations from shore) and the orientation of the playback boat (which in turn influenced the directionality of the underwater speaker) were accounted for in the transmission loss models to provide an estimated RL at each seal location (Figures 3, 4).

## 2.4 | Seal abundance

The relative abundance of seals in the channel was measured using visual observations from a cliff top overlooking the channel between 3 June and 27 July 2013. Scans were carried out during daylight hours between 06.20 and 21.30 hr, at all states of the tide. Visual scans for seals at the water surface within the study area (up to a maximum range of *c.* 2,500 m from the observation locations) were made using binoculars (Monk Nereus 7 × 50) every 10 min, with scans lasting *c.* 5 min in duration, during which the number of seals sighted was recorded; for details on data collection protocols, see Hastie et al. (2016). Further, wind speed and the orientation of the playback boat were noted (for the transmission loss models). Six observers collected data during the study; however, only a single observer collected data within each individual scan. During any one day, the number of scans ranged between 15 and 61 (over a period of between 2.5 and 10.2 hr). Times between these bouts of observations varied between *c.* 1 and 5 days (Figure S1).

## 2.5 | Statistical analyses: Changes in seal abundance

Previous analyses of changes in the numbers of seals sighted in the water from the land-based visual observations showed significant patterns in the numbers of seals sighted with tidal state, time of year, and observer ID. Thus, in addition to our covariate of interest, playback status, we also included these variables here; data and previous analyses are described in detail in Hastie et al. (2016). Playback status was input as a factor variable with two levels ("silent" and "turbine signal"). These analyses were conducted using a general additive model (GAMs; Hastie & Tibshirani, 1990) with a Poisson error distribution and a log-link function within a generalized estimating equation (GEE) framework. The Wald's test (Hardin & Hilbe, 2003) was used to determine each covariate's significance. The GEE framework was required because the data consisted of observations collected close together in time, and consecutive observations are likely to be correlated beyond the underlying processes included in the model, resulting in some residual autocorrelation which violates a key assumption of GAMs. Within GEEs data are seen as a collection of panels within which model errors are permitted to be correlated and between which the errors are assumed independent. Using robust sandwich-based estimates of variance (Pirotta, Matthiopoulos, MacKenzie, Scott-Hayward, & Rendell, 2011), the uncertainty about the parameter estimates returned were robust to the presence of autocorrelation within each panel while not explicitly modelling this correlation. Through an investigation of temporal autocorrelation using the *acf* function within the R "stats" package (R Core Team, 2017), Julian day was chosen as the GEE panel size here (Figure S3); in practice, there were between 1 and 5 days between each playback day.

## 2.6 | Statistical analyses: Spatial responses to playbacks

Changes in the distribution of seals in response to the acoustic playbacks were analysed using the location information from the animal-borne GPS telemetry (Figure 4). The tag data consisted of a series of time-stamped GPS locations when the seal was at the water surface. Due to inherent variability in dive duration, the location data were not regularly spaced. To ensure that these did not bias the analyses (see below), a series of position estimates were derived at regular, 5 min intervals by linear interpolation between cleaned locations assuming constant speed of movement and constant heading between locations. This interpolation interval was chosen to be close to the mean interlocation interval in the raw data (4.9 min; Figure S4); this amounted to a mean of 1,345 (*SD* = 546, range = 268–1,886) locations per seal. Data were limited to interpolated locations when seals were at sea (i.e. not hauled out), and to periods when the 12-hr playback files were being played. Each location was coded as 0 or 1 depending on whether the silent control or the tidal turbine signal was being played at the corresponding time. There were approximately equal numbers of interpolated seal locations during the turbine playbacks (6,905 locations) and the silent controls (6,545 locations).

The purpose of the telemetry data analyses was to address two key questions: (1) did tagged seals show displacement from the playback location and (2) at what distance was any displacement evident. In order to address question 1, we modelled the distance (square-root transformed) of seals from the playback device (m) as a function

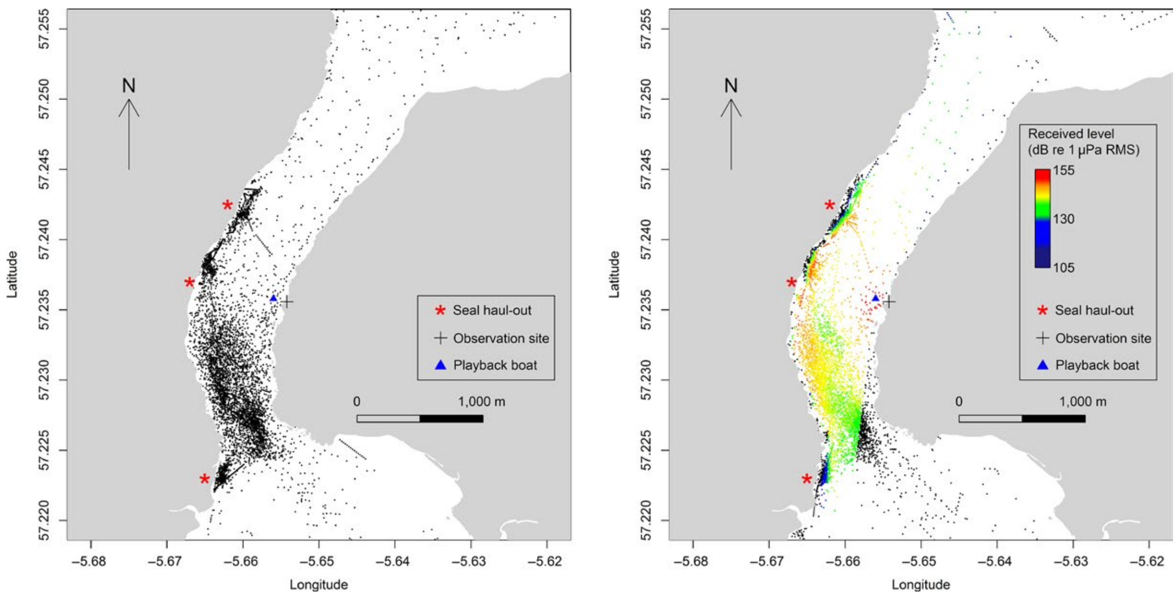


**FIGURE 4** Distribution of seals within the tidal channel during the study. The left panel shows the interpolated locations of seals at 5 min intervals when the playback was a silent control (black points); the right panel shows interpolated locations colour coded by the predicted received levels from the tidal turbine playback (NB locations where the estimated RL is less than 105 dB re 1 µPa$_{(RMS)}$ are coloured black). The locations of the haul outs in the channel are shown by the red asterisks, the location of the playback system is shown by the blue triangle, and the land-based observation location is shown by the cross

of the playback signal (silent or turbine signal) using GAMs with a Gaussian error distribution and an identity-link function within a GEE framework as described above. The GEE panel specified was seal tag ID which meant that confidence intervals were robust to the presence of residual autocorrelation within each seal track. Unlike a mixed effect framework which provides predictions that represent an average (unsampled) seal, the predicted response within a GEE framework is a population mean (i.e. the same as a GAM). The regularisation of locations was therefore also necessary to avoid the predicted mean response being driven by data rich individuals. The Wald's Test (Hardin & Hilbe, 2003) was used to determine the covariate's significance.

To address question 2, we modelled whether or not the turbine signal was being played (0 or 1) as a function of the distance from the playback location (m); effectively, this can be viewed as a comparison of the amount of time seals spent in an area during playbacks with the amount of time spent during the silent controls. A GAM with binomial errors and a logit-link function was fitted within a GEE framework as described above; as the effect of distance was likely to be nonlinear it was input as a cubic B-spline.

The model measures how the number of locations in the turbine playback as a proportion of all locations varies with distance from the playback vessel. If there was no displacement during playback, one would expect a constant probability of *c.* 0.5 at all distances from device and thus no significant effect of distance. Under the scenario that there was displacement, the distance at which the upper 95% confidence interval drops below 0.5 was used to determine the spatial extent of the displacement. The magnitude of displacement at a given distance can be calculated as a percentage change in usage using Equation 1.

$$U = -2 \times (P_n - P_{sig}) \times 100 \tag{1}$$

where $U$ is the percentage change in usage by seals, $P_{sig}$ is the predicted probability that a seal location is within a turbine signal playback period and $P_n$ is the number of seal locations during the silent periods expressed as a proportion of all seal locations; this value (0.5) is effectively the expected proportion of seal locations if no response is observed.

## 3 | RESULTS

### 3.1 | Seal abundance

Relatively high numbers of seals were sighted within the tidal channel throughout the playback trials. Specifically, seals were sighted in the water during 1,068 (96%) of the shore-based scans; the mean number of seals sighted in the water during a scan was 6.6 (*SD* = 5.6) and ranged from 0 to 39. During the silent control periods, seals were sighted during 582 (96%) of the scans; the mean number of seals was 7.0 (*SD* = 6.1) and ranged from 0 to 39. During the turbine playback periods, seals were sighted during 449 (97%) of the scans; the mean number of seals was 6.1 (*SD* = 5.0) and ranged from 0 to 34 (Figure 5). Results of the GAMs showed that observer ID, Julian day and tidal state were all predictors of the numbers of seals sighted in the water; however, playback state (silent control or turbine playback) was not a significant predictor of the number of seals sighted (Table 3).

### 3.2 | Spatial responses to playbacks

All tags continued to transmit during the behavioural response trials and each of the seals was exposed to sound from the playbacks.

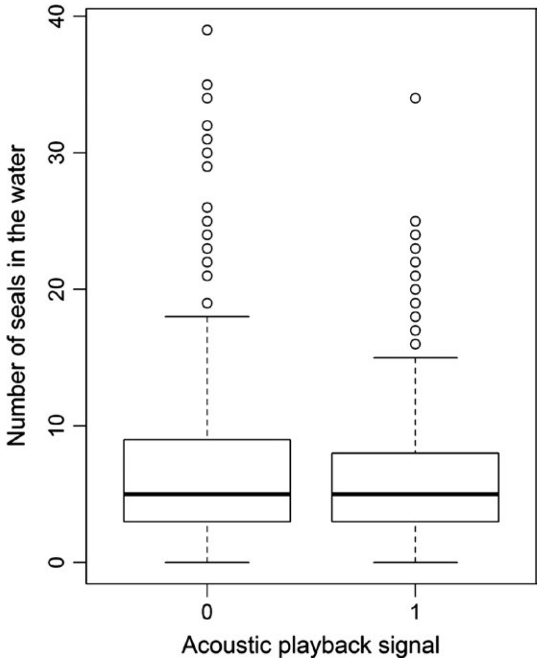


**FIGURE 5** Summary of the number of seals sighted within the channel when playback was a silent control (0) or a tidal turbine (1). The figure shows the median number of seals (solid line), the 25th and 75th percentiles (boxes), the range without outliers (whiskers), and outliers (open circles)

**TABLE 3** Summary of the generalized additive models (GAMs) describing the influence of Julian day, tidal state and the playback signal ("silent" or "tidal turbine") on harbour seal abundance. GAMs within a generalized estimating equation (GEE) framework were used to account for any residual autocorrelation with a GEE panel size of 24 hr (Julian day) being used here. The Wald's test (Hardin & Hilbe, 2003) was used to determine each covariate's significance

| Variable | *df* | $\chi^2$ | *p* |
|---|---|---|---|
| Observer | 5 | 589 | <.0001 |
| Julian day | 20 | 1,863 | <.0001 |
| Tidal state | 4 | 268 | <.0001 |
| Playback signal | 1 | 1 | .34 |

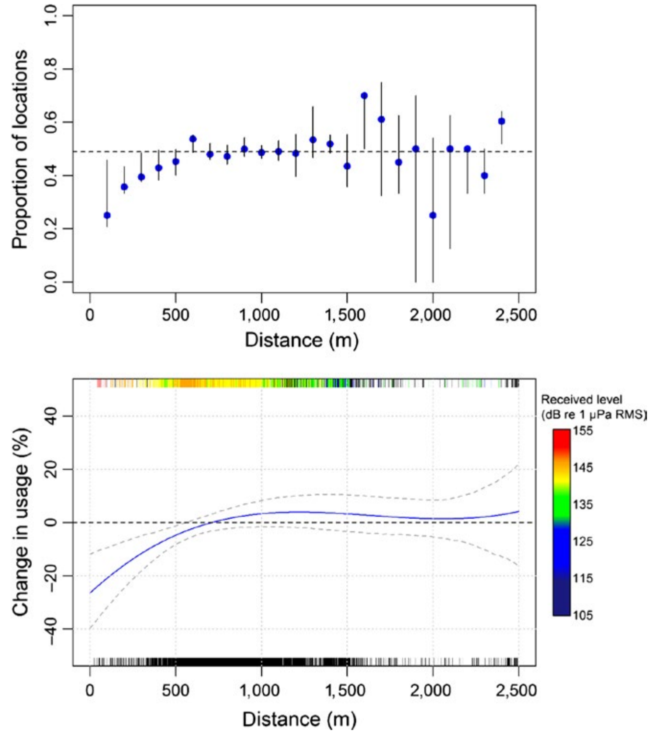


**FIGURE 6** The upper panel shows the number of seal locations within each 100 m distance bin when the turbine signal was played expressed as a proportion of total number of locations in each distance bin; the values represent the median (±IQ range) proportion of locations across all seals. The lower panel shows the predicted change in usage (with 95% CIs; grey dashed lines) with distance (m) from the playback boat. The rug points on the lower graph show the distribution of seal locations with distance from the playback boat during the silent (bottom) and turbine (top) playbacks; rug points for the turbine playbacks are colour coded to show the predicted received level (dB re 1 $\mu Pa_{(RMS)}$) (NB points where the predicted RL is less than 105 dB re 1 $\mu Pa_{(RMS)}$ are coloured black). In both figures, the horizontal dashed line represents the expected value if no response was observed (0.5 in the upper panel and 0 in the lower panel), with a value below these representing an apparent avoidance response

During the turbine playbacks, the maximum estimated RL within the study area (at the seal surface locations) was 157.8 dB re 1 $\mu Pa_{(RMS)}$ with a median level of 140.7 (IQ range 138.3–142.8) dB re 1 $\mu Pa_{(RMS)}$.

Results of the GAMs of seal distance as a function of playback signal showed that there was a significant increase in the distance of seals from the playback location during turbine playbacks ($\chi^2 = 13.1$, $df = 1$, $p < .001$); predicted mean distance was 841 (95% CIs 820–863) m during silent playbacks and 865 (95% CIs 845–885) m during turbine playbacks. Results of the GAMs to test the spatial extent of displacement showed that the distance from the playback location was a significant predictor of the probability that a location was within a turbine playback period ($\chi^2 = 18.4$, $df = 3$, $p = .004$) rather than a silent control period. The relationship was relatively flat at a mean probability of *c.* 0.5 beyond *c.* 500 m indicating no response to playback; however, at closer ranges (<500 m), the mean probability dropped below 0.5 to a minimum of 0.35 at the playback location. In other words, there was evidence that seals exhibited avoidance of the turbine playbacks up to ranges of *c.* 500 m. When expressed as a percentage change in usage, this equates to a decrease in usage of between 11% and 41% ($M = 27\%$) at the playback location (Figure 6). At 500 m from the playback location, usage decreased by between 1% and 9% ($M = 5\%$) during playback (Figure 6). Up to ranges of 500 m from the playback location, the maximum estimated RL (at the seal locations) was 157.8 dB re 1 $\mu Pa_{(RMS)}$ with a median level of 142.4 (IQ range 140.6–144.9) dB re 1 $\mu Pa_{(RMS)}$ (Figure 6). Further analyses to determine the sensitivity of inter-location interpolation interval on the predictions of usage changes showed that for all interpolation intervals tested (120 to 660 secs), distance from the playback location remained a significant predictor of the probability that a location was within a turbine playback period. Further, the pattern of usage change was generally consistent regardless of interpolation interval; however, likely due to the decrease in power, the significance of the relationship generally declined with increasing interpolation interval (Table S1).

## 4 | DISCUSSION

This study is the first to provide empirical measures of the behaviour of marine mammals in response to the sounds of an operational tidal stream energy device. The results showed that harbour seals exhibited localised avoidance of the sounds but that overall numbers of seals within the wider area (a tidal channel 4 km long by 0.5 km wide) did not change significantly.

Overall, the techniques used here worked well for measuring the responses of harbour seals to the acoustic signals of an operational tidal turbine. The combination of animal-borne GPS tags and visual observations from shore provided information on avoidance responses with respect to range from the playbacks and overall changes in seal numbers within the area. The relatively high seal density and strong site fidelity by the tagged individuals in this study area (Hastie et al., 2016) meant that the sample size from both the telemetry study and visual scans were large enough to provide robust comparisons between signal and non-signal periods. From this perspective, it is important to consider that in other areas where the use of an area may be less predictable (where seals may exhibit more wide ranging movements), such tagging studies may not prove as tractable. In contrast, land-based observations are likely to be practical at many coastal sites and with the addition of techniques to geolocate seals at the surface from shore (e.g. Hastie, Wilson, & Thompson, 2003) may also prove practical for measuring spatial responses to the playbacks.

From a policy perspective, the results are important for the prediction of impacts of tidal turbines in coastal waters. Specifically, tidal turbines have the potential to cause physical injury to marine mammals through direct contact with moving structures or parts of the turbines (Wilson et al., 2007). However, the potential for such impacts would be lower if animals exhibited appropriate avoidance responses to the turbines. Responses to tidal turbines can potentially occur at two different scales; at medium ranges of tens to hundreds of metres, animals might avoid the turbine site leading to a reduction in the density of animals and therefore the rate of close encounters. At closer ranges (metres to tens of metres), potentially within the sweep of the turbine rotors, individuals might respond directly to evade collision with the actual blades. The results presented here show that harbour seals do exhibit avoidance responses to the noise from tidal turbines at scales of hundreds of metres with a predicted reduction in the usage by seals of between 11% and 41% at the sound source to between 1% and 9% at 500 m from the sound source. It is important to highlight that the analyses carried out here were based on locations of seals at the surface and it is possible that closer approaches to the speaker were made underwater; however, the relatively short interval between locations here (5 min) is likely to have minimised this potential limitation. The results suggest that, for a turbine with the acoustic characteristics and source level (175 dB re 1 μPa-m$_{(RMS)}$) of the SeaGen turbine, the rate of close encounters between seals and turbines could effectively be reduced by between 11% and 41% as a result of responses to the sound produced. These results could be used as preliminary avoidance rates for predicting the effects of tidal turbines on seals using collision risk models. However, it is important to note that effective avoidance rates will likely increase if seals can visually detect the moving rotors of turbines at close range in time to take appropriate action in order to evade them.

The study site used here is a tidally energetic channel that is used intensively by harbour seals. An array of tidal turbines has also been proposed for this site making it as close to contextually accurate as was currently possible for a study of seal responses to tidal turbine sound. However, the proposed location of the tidal turbines and the main concentration of seal swimming activity were both in a highly localised area in the narrowest part of the channel subject to the strongest tidal currents which was *c.* 700 m from the playback location. This may be important when extrapolating from these data to make predictions of avoidance in other areas. Specifically, the probability of a seal exhibiting a behavioural response to turbine noise through avoidance of an area is likely to be affected, not only by the perceived sound levels, but also by a range of internal factors specific to each individual (such as hunger level, need to haul out, and reproductive status), and external factors such as background noise, availability of prey or intra- and interspecific competition (Götz & Janik, 2010). Given this, the levels of avoidance by seals may be markedly different in areas or at times where their motivation to remain in an area is different. Further, when considering responses to future turbines, it is important to highlight that information on the acoustic characteristics of operational tidal turbines is extremely limited and we only used a single turbine signal; given the wide range of turbine designs being considered (Khan, Bhuyan, Iqbal, & Quaicoe, 2009), it is unclear how representative the signals used in the current study might be for future turbines. However, at least from a source level perspective, limited data would suggest that the signal used in the current study may be relatively high compared to other turbines (Robinson & Lepper, 2013).

In the current study, the median received level within the zone where a significant reduction in usage was observed (~500 m) was 142.0 (range 138.7–157.8) dB re 1 μPa$_{(RMS)}$. Beyond this, the median RL was 140.6 (range 105.7–150.7) dB re 1 μPa$_{(RMS)}$. It is important to place these in the context of ambient noise; previous measurements in the study area ranged between 116 and 137 dB re 1 μPa$_{(RMS)}$ (Wilson & Carter, 2013). This suggests that the signal should have been audible to the seals out to at least the ranges where the responses were observed.

In contrast to many anthropogenic sounds in the marine environment, the tidal turbine sound played in the current study was likely to be a novel acoustic stimulus for these seals. Deecke, Slater, and Ford (2002) showed that the novelty of signals can be an important factor in the likelihood of seals avoiding a sound; their study (Deecke et al., 2002) showed that seals responded to the calls of unfamiliar killer whale (*Orcinus orca*) calls but not to familiar ones. Deecke et al. (2002) highlight that seals probably use selective habituation to reduce the probability of predation; this predicts that seals start with a general acoustic image of a predator or threat from which harmless cues are removed by habituation. This provides benefits by allowing them to learn to only react to genuine threats but initially generates costs by also reacting to false alarms. It does not require experience with the predator, since any unusual cue that falls within a certain predator class elicits a response (Deecke et al., 2002). Therefore, it may be the novelty of the tidal turbine signal played in our study that elicited the avoidance responses shown here and only through exposure to real operating tidal turbines and appropriate monitoring will the long-term nature of their responses to interactions become clear. The policy implications of this potential mechanism are important. We have shown that seals were able to detect and exhibit avoidance of the signal; it is therefore possible that seals encountering real tidal turbines for the first time will correctly perceive them as a threat and become conditioned to avoid the signal. This conditioned response, when combined with habituation, may ultimately lead to appropriate levels of avoidance by seals.

The biological consequences of avoiding a signal produced by a potentially harmful source such as a predator or tidal turbine are clear; the avoidance of these will inevitably lead to a reduction in potential physical interactions or fatalities. However, avoidance at the spatial scales measured here (>500 m) have the potential to lead to more chronic negative effects in certain contexts. For example, there may be costs associated with avoidance if these occur within key foraging areas for seals; avoidance of acoustic signals could lead to increased foraging competition or reduced foraging opportunities. Further, where turbines are deployed in narrow channels, there is the potential that avoidance at these scales could lead to turbines being perceived as barriers to movement through the channels for at least a proportion of seals. Similarly, in areas where arrays of turbines are planned, consideration of the distances between turbines is likely to be important; where inter-turbine distances are less than the avoidance ranges shown here, there is the potential for displacement of seals from the area covered by the array.

In summary, this study has provided evidence that seals can detect the sound of an operational tidal turbine and exhibit avoidance of these up to ranges of 500 m; this effectively reduced the usage by seals within these ranges by 11%–41% at the playback location. This provides important information for regulators and policy makers looking to predict the potential impacts of individual turbines. Specifically, the results suggest that there would be an 11%–41% reduction in the number of seals encountering tidal turbines thus avoiding the potential for physical injury. In practice, this can be used directly as an avoidance rate when predicting the effects of tidal turbines on seals using collision risk models. However, there is now a clear need to measure how marine mammals behave in response to actual operating tidal turbines in order to learn whether marine mammals and tidal turbines can coexist if the large scale arrays of hundreds of turbines currently envisaged for the industry are deployed.

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## AUTHORS' CONTRIBUTIONS

G.H., P.L., D.T., S.B., J.E. and B.W. conceived the ideas and designed methodology; G.H. collected the data and led the writing of the manuscript; G.H. and D.R. analysed the data. All authors contributed critically to the drafts and gave final approval for publication.

## DATA ACCESSIBILITY

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.vt2b3 (Hastie et al., 2017).

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## SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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