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Providing ecological context to anthropogenic subsea noise: assessing listening space reductions of marine mammals from tidal energy devices

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Abstract

The deployment of tidal energy arrays is gaining momentum to provide marine renewable energy (MRE) to the global market. However, there are concerns over the potential impacts underwater noise emissions from operational devices may have on marine fauna. Auditory masking (the interference of important biological signals by anthropogenic noise) is a highly pervasive impact to marine fauna. We used a relatively new approach to evaluate the effects of noise from operational tidal energy devices on the listening space of marine mammals. Here, listening space reductions (LSR) for harbour porpoises (*Phocoena phocoena*) and harbour seals (*Phoca vitulina*) were assessed in winter and summer for two tidal energy devices of different designs. Results demonstrated that LSR was influenced by type of turbine, species, and season. For instance, LSRs for harbour seals were in excess of 80 % within 60 m, whilst for harbour porpoise they were in excess of 55 % within 10 m of the devices, respectively. For both species, LSRs were highest during winter, characterised by low ambient noise conditions. These findings highlight the importance of assessing masking over seasons, as masking effects are highly influenced by ambient noise conditions. Understanding the natural variation within seasons is also particularly relevant for tidal turbine noise assessments as devices are typically situated in highly dynamic environments. Since masking effects occur at the lower level of behavioural impacts in marine mammals, assessing the spatial extent of masking as part of environmental impact assessments is recommended. The listening space formula, which is largely based on measurable environmental factors (device and ambient noise), is transferable to any MRE device, or arrays, for any species (for which an audiogram can be assumed) and therefore provides an effective method to better inform the MRE pre- and post-consenting processes.

Keywords: Hydrokinetics; Harbour Seal; Harbour Porpoise; Renewable Energy; Masking; Acoustics

1. Introduction

The clear link between non-renewable fossil fuels and environmental degradation [1,2] has resulted in a global drive towards electricity generation from renewable sources. The need to broaden renewable energy options, whilst considering societal resistance to expanding wind and hydro developments on land (e.g. [3][4][5]]), makes energy extracted from tides and ocean waves a promising addition to the existing range of renewable energy sources. For these technologies to contribute significantly towards the renewable energy targets for 2050 and beyond, development of commercial wave and tidal arrays capable of generating more than 30 megawatts of electricity per annum would be required [6].

Various prototypes and arrays of two or three wave and tidal devices exist at several locations around the UK and globally (see [7] for full details of developers and their devices). These small-scale arrays provide the opportunity to assess potential ecological and environmental impacts on marine fauna during the early stages of array development. One of the knowledge gaps, for which remains a high degree of uncertainty, is the potential impact of noise generated by marine renewable energy (MRE) subsea structures (i.e. a turbine or other moving components) on marine fauna.

The acoustic frequencies that may be generated throughout the various stages of the installation and operation of tidal turbine devices range between 200 and 8200 Hz (e.g. [8] [9] [10] [11]) [12]). High-energy noises will, for instance, be emitted during the installation and decommissioning of the device(s) (e.g. drilling, cable and chain laying), and the associated increase in vessel traffic during all phases (installation, operation and decommissioning). Throughout the installation phase, exposure to noise will occur over a relatively short period of time and will be intermittent in nature. However, during the operational phase, there will be a near-continuous noise emission from the mechanical working or moving components of the device, such as the gear box [8], mooring chains [10] and/or a tether [13], depending on the device under consideration.

A diverse range of mobile marine fauna frequent highly energetic environments [14], co-occurring with selected MRE sites. Several species of marine mammals and fish are known to have hearing ranges that overlap with the low-frequency noise emitted from tidal turbine devices (see [15] [16] for a review). For example, bottlenose dolphins (*Turiops truncatus*) and common dolphins (*Delphinus delphis*) have shown hearing sensitivities to signals as low as 100 Hz, while killer whales (*Orcinus orca*) show sensitivity down to 500 Hz ([17], [18], [19]). Therefore, auditory masking – the interference of a biologically important signal by an unimportant noise that prevents the listener from perceiving the signal – is expected to occur [17], and is considered the most pervasive impact of anthropogenic noise [16]. Consequently, low-frequency device-generated noise has the potential to interfere with an animal's ability to perceive their natural acoustic environment [16] [18]. The immediate surrounding area where animals can detect biologically-important sounds is referred to as the listening space [20] [21]. As the marine mammal enters a device's noise field, the available listening space around the animal is reduced due to the anthropogenic noise interfering with incoming sounds that are potentially biologically important [21]. Potential consequences include 1) a reduced range (synonymous with area in this context) at which the listener can detect potential prey; 2) predators can get closer to prey before being detected; and 3) distant acoustic cues from conspecifics are not detected. The listening space concept differs from communication space in that it extends beyond intra-specific communication and also includes the detection of acoustic signatures from conspecifics, prey, predators and/or danger. It also differs from the communication space metric by its computation, whereby prior knowledge of the species-specific auditory filter, gain, detection threshold, signal directivity and duration are not needed [22]; indeed, the only species-specific data requirement is an audiogram.

Even in the absence of anthropogenic sources, the ocean is not silent. There are both physically and biologically derived sounds, such as breaking waves and marine life that together form what is referred to as the soundscape. Furthermore, daily and seasonal fluctuations in noise levels will occur due to changes in current speeds, sea state (changes in wind strength and direction) as well as spawning and migration patterns of many marine species [23]. While noise characterisation of high flow environments ($> 3\ ms^{-1}$) remains challenging owing to flow noise over hydrophones, ambient noise is likely to be intensified from sources such as tidally-driven or bathymetry-induced turbulence, sediment resuspension or boulder movement [24] [25]. Therefore, overall soundscapes in marine environments can be classified as broadband, composed of a range of frequencies over the entire frequency spectrum [26]. The overlapping frequencies of natural soundscapes and noise associated with MRE devices has been identified as one of the main challenges when undertaking noise measurements: determining background sound versus the device noise [27].

To date, most empirical research on wave and tidal energy device noise has been limited to the level and propagation (or footprint) of noise from a single device (e.g. [8], [11], [28]). While this body of research has been vital for baseline measurements, it lacked ecological context; that is, how device-generated noise relates to marine fauna listening space. In this paper, we apply the listening space reduction (LSR) method [20] to identify the potential zone of influence for which listening space decay may occur for two marine mammal species around two different tidal energy devices. In addition to device type and species, we assess LSRs in winter and summer to evaluate the influence of season and associated ambient noise levels. Set in a highly energetic tidal environment, we demonstrate the transferability of this approach to the MRE sector, providing a complementary toolset that could better inform the pre- and post-consenting processes.

2.Materials and Methods

2.1 Study Site, Turbine Devices Investigated, and Ambient Sound Levels

Noise levels produced by two sub-sea tidal turbines were assessed in the Narrows tidal channel, located in Strangford Lough, Northern Ireland, UK (N 54° 23.06 W 5° 33.79) (Fig. 1). Strangford Lough is a Special Area of Conservation (SAC) that holds a large breeding colony of harbour seals (*Phoca vitulina*, listed on the Annex II of the EU Habitats Directive). Harbour porpoises, (*Phocoena phocoena*, listed on Annex I of the EU Habitats Directive) are also commonly occurring cetacean species in the Lough [29]. The seafloor of the Narrows consists of cobbles and small to large boulders on a bedrock base layer, with flow rates at the turbine sites reaching approximately 2 ms^{-1} [30]. The two tidal turbines considered in this study were the ¼ scale Deep Green sub-sea turbine developed by Minesto (see [13] for full details on this device, referred to herein as the 'kite'), and the full-scale SCHOTTEL IST device ([8] referred to herein as 'schottel'). The kite consists of a turbine attached to a fixed wing (wing span of 3 m) and flies in a figure-of-eight trajectory using hydrodynamic lift and rudder control. The kite is attached to a foundation on the seabed, at a depth of approximately 20 m, by a 27 m long moving tether. The schottel turbine is a fixed horizontal-axis stationary device, mounted from a moored barge at a depth of 3.4 m below the sea surface over an approximate total water depth of 12 m (see [31] for more details on the schottel device).

The ambient soundscape of the Narrows was recorded for 2 weeks during a summer (July 2016) and a winter (January 2017) deployment, respectively. The ambient sound measurements were undertaken from a passive acoustic monitoring (PAM) station: one located to the southwest of the location of the turbine positions (referred to as the south hydrophone, 54° 22.686 N 005° 34.007 W) and another to the northwest (referred to as the north hydrophone, 54° 23.352 N 005° 34.038 W) (**Fig. 1**). Each PAM station consisted of a single SoundTrap 300HF acoustic recorder (working frequency range 20 Hz – 150 kHz ± 3dB, Ocean Instruments Ltd, Auckland, New Zealand) at mean water depths of 14 and 13 m at the north and south hydrophone positions, respectively (**Fig. 1**). The SoundTrap recorders were programmed to operate on a 50% duty cycle (10min recording every 20min) at a sampling rate of 288 kHz.

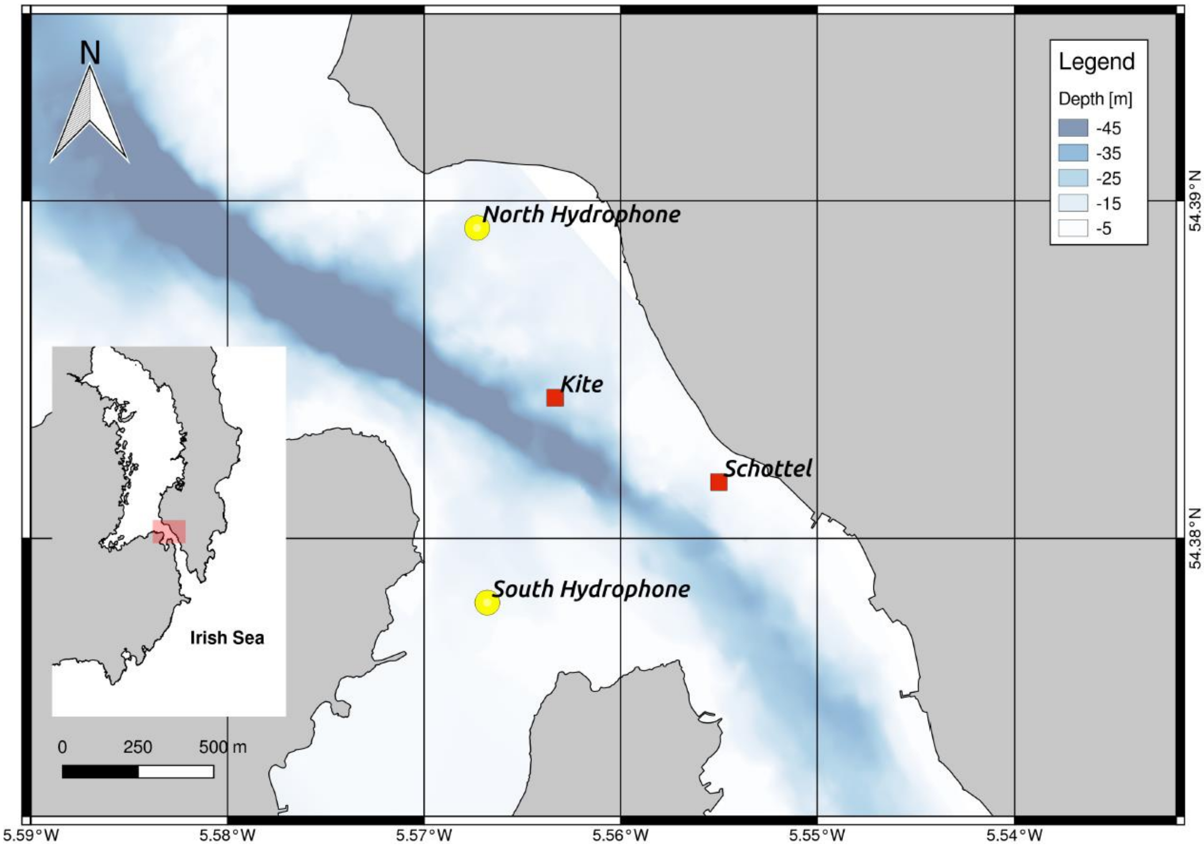

Figure 1. *Location of the north and south hydrophones, collecting ambient soundscape data in July 2016 (summer) and January 2017 (winter), and the location of the kite and schottel devices in the Narrows tidal channel, Strangford Lough, Northern Ireland, UK.*

2.2 Turbine Source Levels

The source levels, in 1/3 octave bands from 50 Hz to 24 kHz, for the kite were back-calculated from *in situ* noise measurements (undertaken during July 2016 and January 2017 [12]), while the source levels for the schottel were taken from [8]. The underwater noise produced from the kite was measured using a drifting hydrophone system, consisting of a

SoundTrap 300 HF autonomous recorder (Ocean Instruments Ltd, New Zealand) secured to a free-floating buoy 2 m below the surface. A depth of 2 m was the maximum allowable depth to ensure the recorder safely passed the kite, since the shallowest point of the kite's flight path was 5 m below the sea surface. An underwater camera (GoPro Hero3^{TM}) was also attached to the recorder to verify that the recorder drifted directly over the path of the turbine. The recording system was deployed 300 m northwest of the operating kite during the mid-ebb tide and retrieved approximately 300 m after passing the kite, constituting a *run*. A total of 24 runs were collected over two successive days. A GPS waypoint was taken at both the deployment and retrieval locations using a handheld GPS (Garmin GPSMAP78).

Source levels (SL_{turbine}) for the kite were back-calculated using the received 1/3 octave band values (RL_{fc}) at the closest point of approach to the kite, and expected propagation loss (*PL*). It is important to note that the measurements contained both the ambient sound and the turbine noise. Due to the short ranges between the kite and receiving hydrophone at the closest point of approach (less than 6 m), *PL* was defined by simple spherical spreading plus frequency-dependent absorption. This can be expressed as:

$$SL_{turbine} = RL_{fc} + PL;$$
$$PL = 20\log_{10} R + \alpha R \qquad \text{eq. 1}$$

where *R* is the range in metres and α is frequency-dependent absorption at *R*. Since *R* at the closest point of approach was much less than the depth, and due to the high angles between the source and receiving hydrophone, boundary effects were expected to be minimal. If the hydrophone passed close enough to the mid-point of the flight path, it was always visible in the footage from the GoPro3^{TM} camera, given that the kite moves in a figure-of-eight configuration. In such cases, *R* could be determined by matching the video's time-stamps with those in the kite's depth data (recorded by Minesto) and the GPS track of the hydrophone. In other cases, when the turbine was not visible in the camera footage, *R* was calculated based on the speed of the drifting hydrophone (calculated using the distance travelled over time) and the corresponding time-stamp of the kite's depth when the recording system passed overhead. The source levels used herein are provided in **Fig. 2**.

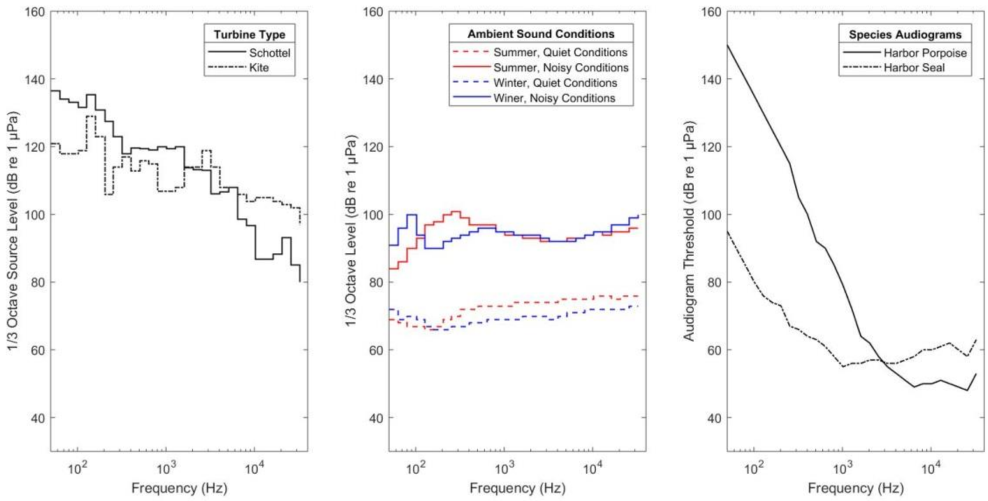

Figure 2. *1/3 Octave Source Level spectra for the Schottel turbine from* [8] *and the Kite from* [12]*, 1/3 Octave Ambient Sound Levels measured in summer (July 2016) and winter (January 2017) (data from this study) and species audiograms for the harbour porpoise and harbour seal, reproduced from* [15] *used for the Listening Space Reduction (LSR) calculations. Quiet and noisy conditions refer to the 5th and 95th percentile ambient sound levels, respectively, calculated over 2 weeks of continuous recording.*

2.3 Calculating Listening Space Reductions

The extent of auditory masking from the two tidal turbine devices was assessed by calculating the listening space reduction (*LSR*), as a percentage, for both harbour seals and harbour porpoises. The algorithm and equations used to calculate the *LSR* follows [21], who define the *LSR* as:

$$LSR = 100(1 - 10^{-2\frac{\Delta}{N}}) \qquad \text{eq. 2}$$

where N is the frequency-specific propagation loss (PL) slope coefficient and Δ is the difference between the ambient noise level (NL_1) and the turbine noise level (NL_2) at a given distance. The two ambient sound levels used in this study were the 5th and 95th percentile levels from the PAM station, respectively referred to herein as quiet and noisy conditions. The value for N was calculated by curve-fitting the modelled PL from the listener's location for each three frequencies inside a 1/3 octave band between centre frequency (F_c) 50 Hz and

32 kHz. Since the listener is moving, *N* will vary as the bearing to the turbine changes. Therefore, *N* was calculated for 72 radials (corresponding to 5 deg bearings) and the *PL* slope was fitted against all radials. The modelling was done using the fully range-dependent parabolic equation (RAMGeo; for frequencies below 1.6 kHz) and ray/Gaussian beam tracing (Bellhop; for frequencies above 1.6 kHz) (see [32] for a review of RAMGeo and Bellhop). The sound speed profile for summer and winter were calculated from spot-measurements at the surface and 1 m above the seafloor using a Valeport CTD (model 602) during ebb tide. The CTD measurements were taken during July 2016 (summer) and January 2017 (winter). Note the CTD measurements were not undertaken at the same depth as the hydrophone used to measure either turbines' source levels. Current velocities were measured with a seabed-mounted broadband 600 kHz RDI Teledyne Workhorse Monitor Acoustic Doppler current profiler (ADCP) installed approximately 30m from the kite's position. Bathymetry data was obtained from the Strangford Lough hydrodynamic model [33] and sediment properties were obtained from [30].

The range over which *N* was fitted was at a distance that represented the listener's maximum listening range under natural sound levels [21], and was defined using the sonar equation without signal gain [34]:

$$SE = SL - PL - NL_1 - DT \qquad \text{eq. 3}$$

where signal excess, *SE*, is set to zero, NL_1 was the 5th percentile sound level of measurements made within the Narrows at some frequency (from the acoustic monitoring station detailed in Section 2.1 above) and the detection threshold, *DT*, was set at 10 dB (following [21], [34], [35] [36]).

As the animal approaches the tidal turbine, the degree of masking will increase. The masking noise level, NL_2, from the turbine was calculated from the turbine's source level (in each third octave frequency band) and the *PL* from the turbine's position to the listener's position:

$$NL_2 = SL_{turbine} - PL_{turbine} \qquad \text{eq. 4}$$

where $PL_{turbine}$ is the modelled *PL* of the turbine noise. Since the listener will always be moving, the NL_2 value will not be constant, and therefore the NL_2 values over the study area are required. These were calculated by modelling the turbine noise footprint using a 1 m grid and 2 m depth resolution, providing a Δ value for each grid-cell. The resulting *LSR* over the same 1 m grid was then calculated (using eq. 7) for each F_c at each 2 m depth-step. The result was a *LSR* map for each F_c between 50 Hz and 32 kHz at each 2 m depth-step. Those maps were then overlaid on top of each other (forming a 3D matrix) and averaged across layers to provide an overall 2D *LSR* map for the study area, for each species. To show the variations in *LSR* between the two turbine types and seasons, a horizontal transect from the turbine's position was taken for 72 radials (every 5 degree bearings), and the corresponding *LSR* values were plotted with logarithm of distance. From those plots, a curve was fitted using a generalised Gaussian model. All processing and data analysis was carried out in Matlab 2017a (The MathWorks, Inc.).

3. Results

3.1 Effects of Turbine Noise on Listening Space Reductions (*LSRs*)

The effects of turbine noise on the listening space varied between the type of turbine, the species, the season and the ambient sound conditions within both seasons. Higher masking impacts, in terms of *LSR*s, were seen for harbour seals, with averaged *LSR*s exceeding 90% within 62 m from the turbine, compared to the maximum averaged *LSR* of 71% within 10 m range for harbour porpoises (**Fig. 3**). The spatial extent of any masking effect also occurred over longer distances for seals as compared to porpoises (**Fig. 4, Table 1**). For example, the maximum distance within which *LSR*s were more than 10 % ranged between 2.3 and 2.5 km for the harbour seal, but between 1.5 and 1.7 km for the harbour porpoise, depending on the type of turbine (**Fig. 4**).

For harbour seals, the distance from the turbine at which *LSR* decreased to zero was larger for the schottel than for the kite (**Table 1**). For harbour porpoises, turbine type had the reverse effect, where the distance at which *LSR* decreased to zero was larger for the kite than for the schottel. Also, the rate at which listening spaces decreased with distance between the two turbine types was not equal, particularly with regard to harbour seals (**Fig. 3**). For example, the *LSR* in harbour seals decreased more rapidly (i.e. a steeper *LSR* curve, see **Fig. 3**) with distance from the kite, than it did for the schottel turbine. This was indicated by higher *LSR*s within 100 m from the kite (of over 80% *LSR* compared to 70-80 % at the same distance from the schottel). However, the maximum masking effect range was 3 km for the kite, compared to 3.3 km for the schottel (**Table 1**). This was due to the differing turbine noise spectra in relation to the species hearing thresholds.

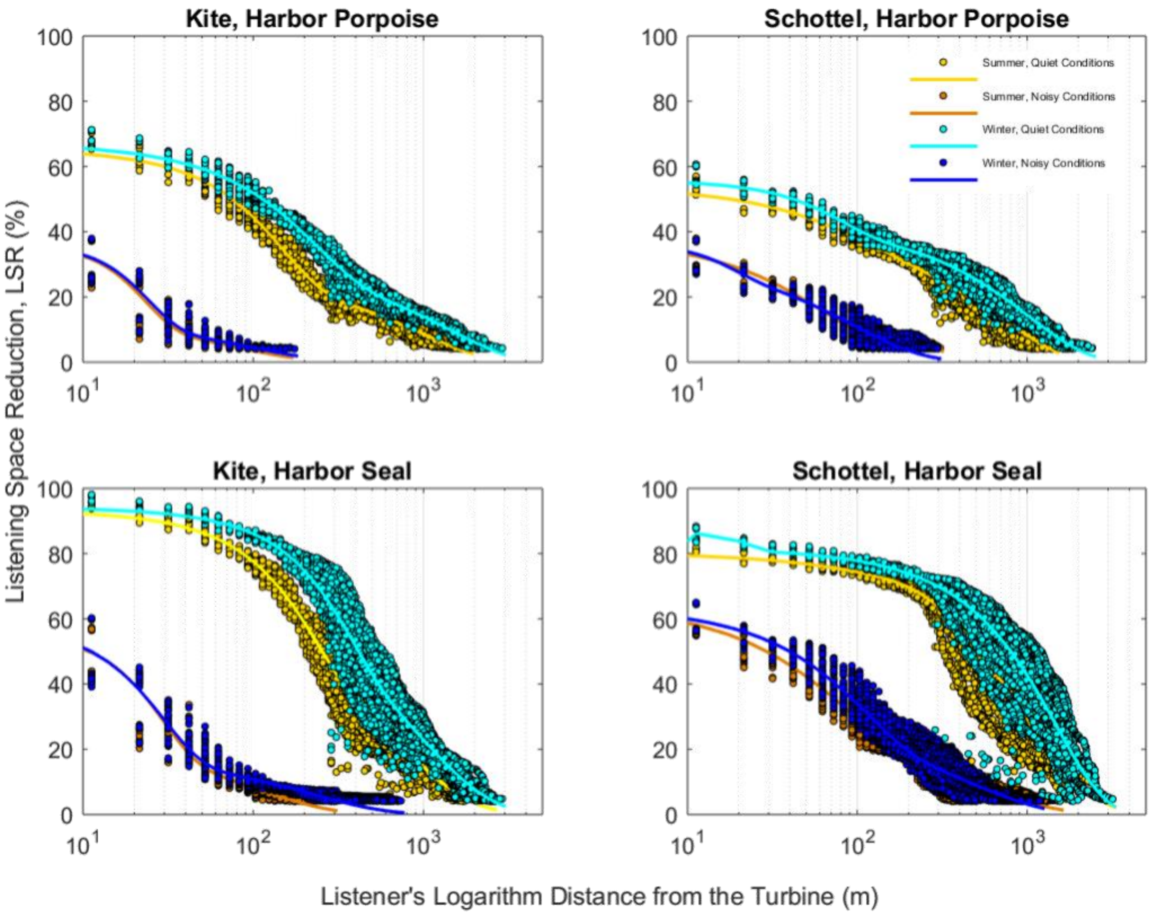

Figure 3. *Listening space reductions (%) with distance from the turbine along 72 radials under varying ambient noise levels (the 5^th^ and 95^th^ Percentiles, referred to as quiet and noisy conditions, respectively) during the summer and winter for the kite (left column) and schottel turbine (right column) for harbour porpoises (top) and harbour seals (bottom).*

3.2 Effects of Seasons on *LSRs*

The greatest masking effects, in terms of *LSR*, were seen during the winter, with higher *LSR* values at closer proximity to the turbines (**Fig. 3**). The change in seasons had less influence on the *LSR*s for harbour seals than for harbour porpoises. For example, the maximum range within which some reduction in listening space for harbour porpoises occurred (i.e. *LSR* was greater than zero) increased by approximately 1 km (based on the extrapolated *LSR* curves in

Fig. 3) during the winter, compared to approximately 100 m for harbour seals (**Table 1**). Generally, the maximum distances from the turbine at which either species started to experience any *LSR* were larger during the winter.

3.3 Effects of Ambient Sound Conditions on *LSR*s

Within seasons, the ambient sound conditions had substantial influence on *LSR*s for both species. The extent of masking, in terms of *LSR*, was greatest during quiet conditions (represented by the 5th percentile ambient sound level) as compared to noisy conditions (represented by the 95th percentile ambient sound level). The differences in *LSR*s between the two ambient sound conditions were larger for harbour seals than for harbour porpoises. For example, at 100 m, the difference in *LSR*s between the two ambient sound conditions was 75 % for harbour seals, but approximately 46 % for harbour porpoises. Changes in the ambient sound conditions had greater effects on the *LSR* at greater distances due to the higher Δ values occurring nearer the turbine as compared to further away [21]. Masking effects, in terms of *LSR*, were substantially greater under quiet conditions, for both turbine types and species.

Turbine Type	**Species**	**Season**	**Distance from Turbine (m)**		
			50 % LSR	**25 % LSR**	**0 % LSR**
Kite	Harbour Porpoise	Summer	83	226	1975
		Winter	113	358	3026
	Harbour Seal	Summer	257	590	2694
		Winter	413	890	3048
Schottel	Harbour Porpoise	Summer	20	340	1534
		Winter	42	490	2471
	Harbour Seal	Summer	520	1186	3155
		Winter	808	1473	3337

Table 1: *Distances at which 50, 25 and 0 % listening space reduction (LSR) occurs for harbour seals and harbour porpoises from two types of tidal turbines during the summer and*

winter. The LSR values are based on the 5th percentile ambient sound level, referred to as quiet conditions, and the range at which 0 % LSR occurs is the spatial limit for masking effects. All distances at which 50, 25 and 0 % LSR occurs are based on the fitted Gaussian curve of all frequency-averaged LSR values across all 72 radials in Figure 3.

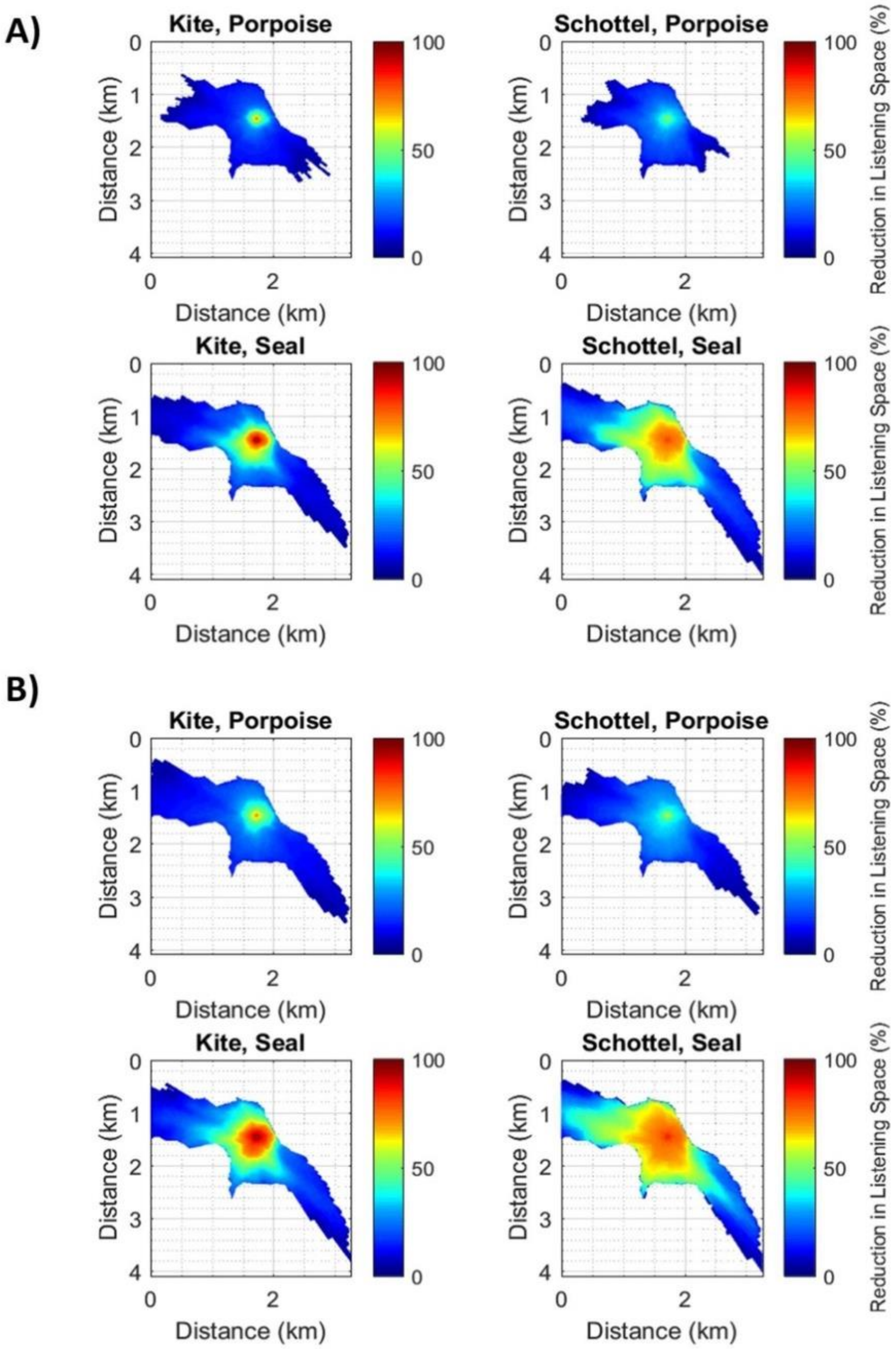

Figure 4. *The spatial exent of masking in terms of listening space reduction (LSR), from the kite (left column) and schottel turbine (right column) under quiet conditions (A) during the summer in July 2016 and (B) during the winter in January 2017.*

4. Discussion

Understanding the spatial extent and auditory influence /ecological impact of MRE device noise as part of environmental impact assessments (EIAs) is fundamental for the conservation of marine mammals that occupy the same environment. In applying a relatively straight-forward analytical approach to assess the effects of noise from two tidal energy devices on the listening space of two marine mammal species, we have shown that listening space reduction (*LSR*) is species- and device-specific, and influenced by the variation in ambient noise across seasons. In all species-turbine scenarios investigated, we found greater masking effects in winter (corresponding to lower ambient noise), which overall had a greater effect on the *LSR* for the harbour porpoise than for the harbour seal. Previous studies have quantified noise emissions from MRE devices to better understand the potential environmental impacts that turbine noise may have on sensitive marine life (see [8]**,** [11]**,**[28]). However, studies aimed at providing ecological context to empirical turbine measurements are rare. The results presented herein are a step forward in providing some ecological context to the standard acoustic propagation modelling. To do this, we adapted an alternative approach to assessing auditory masking as presented by [21] to generate maps showing the effects of turbine noise in reducing the available listening space within which marine mammals can hear potentially biologically important signals.

A range of marine mammal species show sensitivity to underwater noise (see [37], [38], [39], including noise from tidal turbines [40]. This study focused on two model species, the harbour porpoise and harbour seal. Both of these species occur in UK waters and extensively use tidally-energetic environments, thereby resulting in a spatial overlap with potential tidal turbine sites [14], [41], [42], [40], [43]. Harbour porpoises are considered to be particularly sensitive to underwater noise, for example, this species has been shown to have strong stereotypical responses to vessel noise [44], including behavioural responses such as vigorous fluking, bottom diving, disrupted foragaging and even cessation of echolocation [45]. These behavioural responses may impact forgaging efficiency [45]. Since behavioural effects generally occur at higher levels of masking, understanding the spatial limits of masking and how they change over time (for example between seasons and/or extreme weather events) is fundamental. The *LSR* algorithm allows for this, using data that are often requested as part of the pre- and post-consenting phase for tidal turbine devices.

Given marine mammals' reliance on using sound for critical life processes, reductions in listening space can be detrimental to an animal's net fitness (see [16]). The extent of masking by any MRE device, in terms of *LSR*, is dependent on the device's noise spectrum (**Fig. 2**), the source levels of the biologically important signal, the rate of propagation loss, and the frequency-dependent hearing sensitivity of the listener. Frequency-dependent hearing has been studied for both these species, with their respective audiograms revealing more sensitive hearing in frequencies below 2.5 kHz in harbour seals (57 – 95 dB re 1 μPa) compared to harbour porpoises (58 – 140 dB re 1 μPa) (**Fig. 2**). However, above 3.2 kHz, harbour porpoises are more sensitive than harbour seals. Therefore, since the noise from the schottel turbine was largely low-frequency, with little energy above 5 kHz, harbour seals experienced higher averaged *LSR*s at all distances compared to harbour porpoises. However, higher *LSR*s for both species were seen for the kite, for which, the characteristic hydrodynamic noise from the wings and tether resulted in a wider bandwidth as compared to the schottel (**Fig. 2**). Therefore, the spatial extent of masking effects is contextual, based on the frequency content of the biologically important signal the animal is listening for at the time, and the type of turbine in the area. For example, breeding harbour seals call between 40 and 500 Hz [22] and therefore, a larger area of masking would be expected from the schottel turbine (as most energy from the schottel is in the lower frequencies) than for the kite in that context (**Fig. 5**).

While little empirical data from full-scale tidal turbines have been documented in the scientific literature, there is evidence that noise effects on marine animals from a single operating MRE device is less than minor [46]. The source levels of either turbine type considered herein were relatively low, particularly in relation to the receiving soundscape and audiograms of harbour porpoise and harbour seals. However, much of the previous research, including this study, considered noise effects from a single operating device, and have not made an assessment on the cumulative noise effects from full-scale arrays [47]. When multiple devices operate in an array (in relative proximity), the radiated noise field becomes far more complicated [48]. Playback experiments using a digital analogue of a horizontal axis tidal turbine (the *SeaGen* device, operating in 3 ms^{-1} flow) showed an accumulation of sound from the two transducers [46]. Therefore, some concern remains for large-scale turbine arrays consisting of hundreds of devices. Some of those concerns include potential barrier effects, which could be auditory (i.e. far-reaching impact zones, within which *LSR* is expected) [40] or physical (for example, the spacing of devices restricts animal movement). There are in-combination considerations too, for example, when planning arrays in areas with high shipping activity, such as the Irish Sea or English Channel . Quantifying the range-dependent *LSR*s could be useful for informing marine spatial planning and design of arrays, at least from an ecological perspective. For a preliminary assessment of noise footprints from full-scale turbine arrays, the masking noise level (the NL_2 variable in the calculation of Δ, eq. 7) could be adjusted by adding 10*log10(number of devices) and the *LSR* be recalculated. Since that would not consider the spatial extent of an array, it would be a high-level and simplistic estimate from the centre of the array only. For a more robust assessment, the cumulative noise field from the turbine array would need to be modelled for multiple sources operating simultaneously to provide a more accurate masking noise level, NL_2.

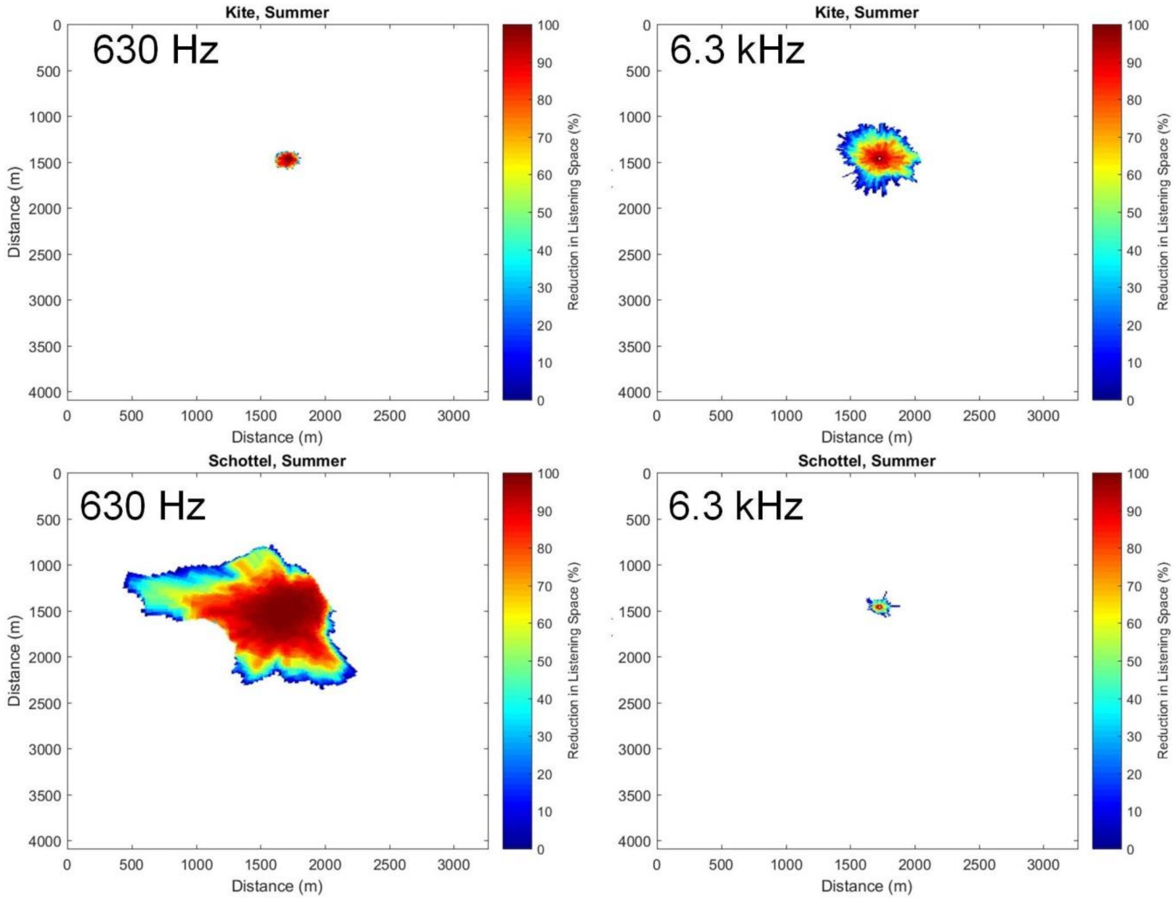

Figure 5. *The extent of LSRs in harbour seals for two frequencies under quiet conditions. Harbour seals have higher hearing sensitivity at 6.3 kHz than at 630 Hz, and therefore LSRs are seen over a larger area at 6.3 kHz for the kite (top right). The opposite is true for the*

schottel (bottom right), the spectrum of which shows higher energy in the lower frequencies, and therefore greater masking is seen at 630 Hz than at 6.3 kHz.

As would be expected, seasonal variation in ambient noise did influence the listening space and, in all scenarios investigated, the spatial extent of masking (in terms of *LSR*) was highest during quiet conditions in winter. While it has been recognised that ambient noise should be characterised during field investigations of MRE sites [46], in this study we further included variations in the ambient sound as a function of season. This approach therefore considers the temporal variation in the ambient soundscape due to the occurrence of marine organisms and local vessel traffic. For example, the main source of noise in summer in Strangford Lough is likely due to the increased recreational vessel traffic, which in-turn increased the ambient noise levels in several frequency bands during the summer, as compared to the winter (see **Fig. 2**). These increases in ambient levels led to the decreased extent of *LSR* zones, because the Δ value in the *LSR* equation (eq. 7) was smaller. The implication of this work is that the listening space for animals around MRE devices will change depending on the time of year. As such, this approach could be used to identify time periods when testing tidal turbine devices would have less of an impact on the listening space of marine mammals.

The ambient noise levels used for this study were obtained from the average of two locations within the study area. However, tidal turbine device sites are often very dynamic in their flow rates, with eddies and turbulent waters acting against the seafloor, submerged rocks and coastlines. Given the importance of the perceived ambient sound level by an animal in the *LSR* calculation, two hydrophones on either side of the Narrows were used to obtain a measurement that incorporated the variation between the two locations. However, both hydrophones were in sheltered areas of the Narrows, outside the main flow, to control for pseudo-noise (noise generated at the hydrophone due to turbulent flow that prevents accurate measurement of true ambient sound levels [49]). This could mean that the ambient sound levels used in this study are different to what a passing animal would experience directly in the near-field of the device. While in regions with relatively homogeneous soundscapes, a generalized measurement would be appropriate. However, within high energy environments (relevant to most tidal turbine sites), it would be recommended that a suite of ambient noise measurements using drifting hydrophones be incorporated into the ambient soundscape analysis.

A key benefit of the *LSR* algorithm is that it only requires quantification of the change to the listener's perceived soundscape. Furthermore, changes to the listening space (as a fractional decrease to the original listening space under ambient sound conditions) as the animal swims past an operating MRE device can be calculated with only minimal knowledge of the listener's hearing abilities. The only requirements for the *LSR* algorithm are the change in masking noise levels (the MRE device's noise field and ambient sound levels), the bandwidth of the biologically important signal (such as the call from a conspecific or prey so that the frequency-dependent propagation coefficients (*N*) can be calculated), and the species' audiogram [20][21]. This is the key advantage to the *LSR* method, as its parameters are predominately environmental and typically obtained during environmental impact assessments for tidal turbine device arrays (for example, collecting baseline ambient noise data and noise modelling) and during the post-consent phase (i.e. recordings of operational noise of the tidal turbine(s)). Notwithstanding, there are a number of underlying conditions and assumptions that need to be understood when applying it to other environments and devices. The device's noise field (i.e. the masking noise level (NL_2 variable in eq. 3)) and ambient sound levels will change with the environment. If no audiogram is available for the species in question, the audiogram of the closest phylogenetic relative may be used, or modelled audiograms, as in the case of large baleen whales where no audiograms exist [21], for instance.

In addition to its applicability to cumulative noise assessments, as well as multiple taxa and regions, the *LSR* method is also transferable to any MRE device type. Once the propagation loss coefficients for the particular region is known, measurements of the local ambient soundscape and audiograms of the species of concern are available, the approach presented herein provides the MRE industry and regulatory bodies with an effective way of translating predictive noise propagation models, commonly provided as part of the EIA process, to zones of influences for which a level of masking may occur. This is a noteworthy step towards predicting how noise generated by tidal turbine arrays may influence the movement and behavior of species of concern.

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