Animal Biotelemetry

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Gone with the wind: environmental variation influences detection efficiency in a coastal acoustic telemetry array

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Abstract

Range tests play a critical role in designing acoustic telemetry studies, guiding equipment configuration, deployment techniques, and the analysis of animal movement data. These studies often strive to capture the effects of environmental variation on detection efficiency over time but are frequently limited in spatial and temporal scale. This could lead to disparities between test results and the circumstances encountered during animal tracking studies. In this study, we evaluated detection range and efficiency at two distinct spatial and temporal scales in a dynamic intertidal ecosystem. Two range tests were conducted, the first being a small-scale study using 6 receivers deployed over 1 month. Using modern acoustic receivers with built-in transmitters and environmental sensors, we then conducted a large-scale range test with 22 receiver stations over a full year to approximate the area and duration of a typical animal movement study. Differences in detection range between the two studies occurred as a result of environmental variation and tag power output, with midpoint ranges estimated as 123 m (small scale, low power), 149 m (small scale, high power) and 311 m (large scale, very high power). At both scales, wind speed emerged as the most influential factor explaining temporal variation in predicted detection efficiency. However, this effect was modulated by wind direction which varied as a result of land sheltering and fetch between the two study scales. At the small scale, detection efficiency decreased with winds from the south and east, while at the large scale, northern and westerly winds were most detrimental. Water temperature had a positive effect on predicted detection efficiency at both scales, while relative water level was positive at the small scale and negative at the large scale. Additional factors, including precipitation and Topographic Position Index, were found to influence detection efficiency at a large scale. Moreover, sensors associated with receivers in the larger array revealed the significant influences of receiver tilt and ambient noise. These discrepancies in the outcomes of the two studies underscore the critical role of scale in range test design and emphasize the need for long-term, in situ range testing at relevant spatial scales.

Keywords Acoustic telemetry, Range test, Detection range, Detection efficiency, Environmental variability, Coastal ecosystem

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Background

In aquatic environments across the globe, acoustic telemetry is currently being used to record the in situ movements of animals across a wide range of taxa, age classes, and sizes [1, 2]. Among the key advantages of this methodology is its versatility, with equipment well suited for a range of habitats from freshwater to marine and array designs that can be adapted to address a multitude of research questions across geographically distinct study habitats [3]. However, with these diverse applications and study environments come a variety of environmental factors whose influence on equipment functionality is still poorly understood.

Acoustic telemetry relies on the transmission and detection of ultrasonic signals through water to one or more acoustic receivers. Individually coded acoustic transmitters (or tags), which are attached to or implanted in target animals (*e.g.,* often in the body cavities of fish), produce a series of pings at a specific frequency (typically 69 or 180 kHz) which must be detected in its entirety to be accurately decoded and archived by an acoustic receiver. As acoustic signals degrade in amplitude and structure as they disperse through an environment [4], the relationship between detection efficiency (*i.e.,* the probability of detecting tag transmissions) and distance, referred to as detection range [5], is among the most meaningful factors considered for array design and performance. This is of particular importance in open study environments where tagged animals may not be confined within close proximity of acoustic receivers.

The distance at which a tag transmission can be detected by a receiver is partly determined by the strength and frequency of the emitted signal, along with a suite of factors that affect the transmission of sound through aquatic environments. Acoustic signal intensity diminishes according to geometric spreading, with factors such as scattering and absorption potentially increasing the rate of decline, particularly for higher frequency sounds [6–8]. Numerous environmental factors are linked to patterns of scattering and absorption, thereby modifying this distance across space and time. Characteristics, such as bottom substrate, bathymetry, and various water column properties (*e.g.,* stratification, bubbles, and turbidity), can disrupt transmission through scattering and absorption, as well as via the refraction and reflection of sound signals [6, 7, 9–11]. Ambient noise in the study environment, caused by either environmental (*e.g.,* wind, waves, rain), biological (*e.g.,* animal noises), or anthropogenic sources (*e.g.,* boats or mechanical noises) can also mask or disrupt the transmission of acoustic signals [4, 9, 12–14]. In some cases, features of mooring design and receiver attachment, including position of the receiver in the water column, receiver tilt, and noise produced by the mooring itself, can also play a major role in receiver performance [15]. The conditions affecting both ambient noise levels and acoustic signal propagation in aquatic systems vary widely over spatial and temporal scales, resulting in differences in detection efficiency as demonstrated by a number of previous studies [5, 12, 16, 17]. As such, there is still some debate surrounding the generalizability of models used to analyze the relationship between detection efficiency and environmental factors across telemetry studies [5, 12].

Prior knowledge of the variability of detection range and efficiency in a given system is critical for the accurate interpretation of animal detection data, as fluctuations in receiver performance can mask or mimic behavioral trends in study animals (*e.g.,* diel activity patterns) [14]. To estimate detection range and account for local spatial and temporal variation in environmental conditions and detection efficiency, telemetry researchers typically conduct small-scale range tests in a representative area prior to initiating a study in a new location [5]. Notably, in most studies, fluctuations in environmental conditions, such as those previously mentioned, mean that detection range is unlikely to remain static over a study's duration. The reported detection range thereby represents an estimate based on the set of environmental conditions encountered within the specific temporal and spatial extent in which the range test was conducted. This implies that certain spatial or temporal features that could affect detection efficiency have the potential to be excluded from initial range testing. The exclusion of environmental conditions occurring over spatial and temporal scales exceeding those included in the range test could lead to type I or type II errors in later analyses of animal tracking data. Advances in acoustic telemetry devices are increasing the ease with which range tests can be conducted and allow simultaneous data collection for a range of potential factors. Newer generations of acoustic receivers can be combined with various sensors such as receiver tilt, ambient temperature, and ambient noise levels, along with sync tags (internal transmitters) that aid in the simultaneous collection of detection records and environmental data. Given the overlap between the detection radii of neighboring receivers, often achieved using grid or gate designs, continuous detection records can be compared among receiver pairs. These datasets can then be analyzed alongside concurrent environmental records and receiver diagnostic data to identify potential correlations with variation in detection efficiency [10, 15, 18]. These functionalities ultimately streamline range testing, reducing the need for additional equipment and manual labor, and facilitating their implementation at larger spatial and temporal scales. Importantly, by simplifying the process of range testing, this advanced equipment may further encourage the transition from preliminary range tests to assessments of detection range and efficiency at spatial and temporal scales aligning with animal tracking studies. This approach will ensure that the effects of environmental factors that vary throughout space and time are more accurately considered, leading to improved validity of animal tracking data.

In this study, we investigate how a wide range of local environmental conditions influence detection efficiency by conducting two range tests of varying spatial and temporal scales in a shallow coastal habitat, the western Dutch Wadden Sea (< 30 km from the mainland, average depth of intertidal area = 3.5 m, average depth of deepest inlet = 25 m; see Methods for further details) [19]. Specifically, our goal was to determine how receiver–tag distance and environmental variation influence detection efficiency in a coastal area subject to dynamic tidal, oceanographic, and meteorological fluctuations. First, we determined how detection efficiency decreases with distance from an acoustic tag at a small spatial and temporal scale (6 receivers deployed over 7.5 km^2 for 25 days) and examined the additional effect of tag power level (high *vs.* low) on the resulting detection ranges. At this small scale, we then examined how spatial and temporal variation in environmental conditions (*e.g.,* bottom depth, wind speed and direction, and water level) affected detection efficiency over time. Second, to encompass a broader range of receiver–tag distances and environmental variability, two subsets of receivers from a large-scale acoustic array were used to examine the effect of distance and environmental conditions on detection efficiency at greater a spatial and temporal scale (51 stations over 1243 km2 for 381 days, and 22 stations over 500 km2 for 373 days). Finally, detection range and efficiency were examined at both small and large array scales to determine whether differences in detection range and efficiency might result from increased variation in explanatory factors.

Methods

Study area

The Wadden Sea is the world's largest intertidal habitat and is protected as a UNESCO World Heritage Site due to its vast importance both for local marine fauna and a range of migratory birds, marine mammals, and fish [20, 21]. This well-mixed intertidal environment is situated between the north coast of the Netherlands and a chain of barrier islands known as the Frisian or Wadden islands. It is characterized by tidal exchange with the North Sea via a series of inlets located between the islands, in addition to freshwater inputs from discharge points along the northern Dutch coastline [22]. Approximately 50% of the trilateral Wadden Sea (extending from the Netherlands to Denmark) is covered by an extensive array of intertidal mudflats which are exposed at low tide and separated by networks of gullies [23]. In shallow waters, environmental factors influencing the upper water column, such as changes in temperature and wind, can have profound impacts on temporal variation in signal attenuation [7]. Spatially, attenuation is affected by bottom substrate (soft, rocky), boundaries, and barriers, and is generally greater in shallow (littoral) waters than in open waters [3]. The extremely shallow depths and tidal variation make this a relatively unique system in which to examine variation in detection range and efficiency.

Array design

The design of the acoustic receiver array used in this study was tailored to research questions pertaining to the use of the Wadden Sea by migratory fish. Specifically, the so-called Swimway array was established as part of the Waddentools Swimway Waddenzee project (https://swimway.nl/?lang=en), aimed at addressing conservation concerns for declining local fish populations [24–26]. In December 2020, prior to the deployment of the complete array, a temporary, small-scale range test array was established in the Marsdiep channel (Fig. 1b). In May 2021, the complete array, consisting of approximately 100 receivers, was deployed in the subtidal gullies of three tidal inlets (Marsdiep, Eierlandse Gat, Vlie; 1529 km^2) (Fig. 1a). For the current study, we incorporate data from the small-scale range test array (7.5 km^2), as well as those associated with two subsets of receiver stations from the large-scale array (51 stations over 1244 km^2 and 22 stations over 500 km^2) (Fig. 1c).

To examine how environmental factors affect detection range and efficiency at two spatio-temporal scales, a static range test design was used, wherein both receivers and tags remained in fixed positions throughout the study. First, a small-scale test array comprised of 6 receiver stations with associated test tags was established in the Marsdiep channel of the Western Dutch Wadden Sea (Fig. 1b). This array location was chosen as a representative for the high-current strengths experienced in tidal inlets throughout the Dutch Wadden Sea (reaching periodic tidal current amplitudes of 1.25 ms^{-1}) [22] and due to its close proximity to the research institute which facilitated easy access to the array. By placing receivers in this area of high wind and current exposure, our goal was to derive a precautionary estimate of the most challenging conditions and therefore potentially the most reduced detection efficiency that could be expected over the full array area. A study duration of 25 d (from Dec 8, 2020 to Jan 2, 2021) was chosen to encompass a range of environmental conditions that could affect detection efficiency, including infrequent or severe weather events. To evaluate resulting changes in the maximum detection ranges,

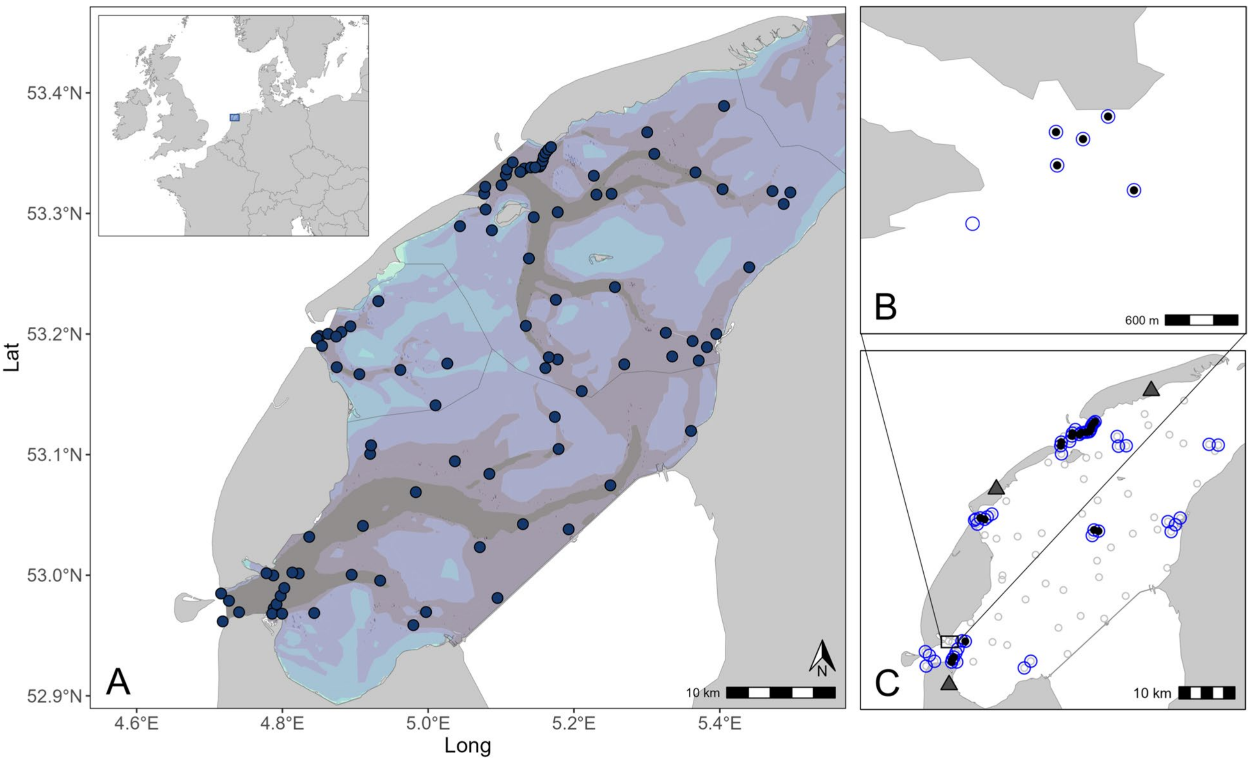

Fig. 1 Map of the Swimway acoustic receiver array, located in the western Dutch Wadden Sea. **A** Blue points indicate individual receiver stations. Tidal basins are indicated by gray lines and bathymetry is colored from light (shallower) to dark (deeper) as per depth codes provided by [27]. **B** Locations of 6 temporary receiver stations in the small-scale range test array used for the small-scale dose–response curve (blue outline) and 5 stations used for the small-scale GLM (filled black points). **C** Locations of all receiver stations in the Swimway array (hollow circles), showing the 51 stations selected for use in the large-scale dose–response curve (blue outline) and 22 stations used in the large-scale GLMM (filled black points). Filled triangles indicate the locations of KNMI weather stations

an array configuration was chosen to provide a range of distances between individual test tags and receivers. The placement of telemetry equipment was dictated by the locations of existing deployment structures in the study area, resulting in a range of 15 fixed distances from 231 to 1431 m (Table 1).

In addition to the small-scale range test, a subset of receivers from the expanded Swimway array was used to increase the range of receiver–tag distances available for analysis and spatial coverage over the study area. These receivers were equipped with integrated sync tags, allowing them to fulfill the same purpose as the range test tags employed in the small-scale study. Of the complete array, 51 receivers recorded detections from neighboring stations and could be used to estimate detection range (Fig. 1c). Due to a lack of sufficient detections at extreme distances at both array scales, receiver pairs with distances exceeding the maximum detection ranges (5% of transmissions detected) calculated for small and large scales, respectively (see Results), were not included in

Table 1 Matrix of Euclidean distances (m) between acoustic receivers (R1–R6) and test tags (T1–T6) in the small-scale range test array

	T1	T2	T3	T4	T5	T6
R1	0					
R2	670	0				
R3	275	806	0			
R4	305	598	231	0		
R5	852	1366	1026	1153	0	
R6	584	647	451	279	1431	0

subsequent analyses of the influence of environmental variation on long-term detection efficiency. Instead, the detection datasets were divided into subsets including a total of 5 receivers at the small-scale (excluding receiver R5) and 22 receivers at the large scale (Fig. 1c). Selected stations in the large-scale study were deployed for a duration of 373 d (May 5, 2021–May 12, 2022), here used to encompass year-round variation in local environmental conditions and infrequent weather events.

Receiver and tag deployments

Acoustic receivers and range test tags were attached to fixed navigational structures which served as platforms of opportunity and included two types of anchored floating buoys (large buoys and spars) and vertical metal poles driven into the seabed (Fig. 2) (for further details on deployment designs, see Additional file 1). In the small-scale array, acoustic receivers and range test tags were attached either: (i) to large floating buoys deployed above relatively deep water (− 14 and − 22 m NAP; Fig. 1) with receiver hydrophones pointed downward ~ 2 m below the surface ($N=2$; Fig. 2a), (ii) to fixed metal poles with receivers positioned near the seabed and hydrophones pointed upward ($N=3$; Fig. 2c), (iii) or in one case, in a similar manner as the metal poles, but with the upper end of the rope attached to a nearby jetty used for environmental monitoring (NIOZ jetty). In the latter two cases (metal pole and jetty deployments), receivers were deployed near the bottom at shallow depths (− 2 to − 7 m NAP, Fig. 1). It should also be noted that due to these shallow bottom depths, bottom-associated (upward-pointing) receivers were still within ~ 2 m from the surface.

All receivers in the large-scale array were deployed on either large buoys or on slightly smaller floating buoys known as spars ($N=51$ for detection range analyses; $N=22$ for detection efficiency analyses; Fig. 2b). Receiver deployment was restricted to buoys located in the intertidal gullies to ensure that receivers would not become exposed to air at low tide (Fig. 1a). Notably, both buoys and spars were freely rotating at the surface, resulting in inconsistent signal shadowing between receiver pairs.

Receiver and tag programming

All tags, receivers, and associated software used in this study were produced by InnovaSea Systems Inc. (Bedford, NS, Canada). For the small-scale range test, each of the 6 receiver stations were equipped with a VR2W single channel omni-directional acoustic receiver and a 69 kHz V13 test tag. To prevent transmission collisions, test tags were programmed to transmit at random intervals between 210 and 270 s. Test tags were also programmed to alternate transmissions between

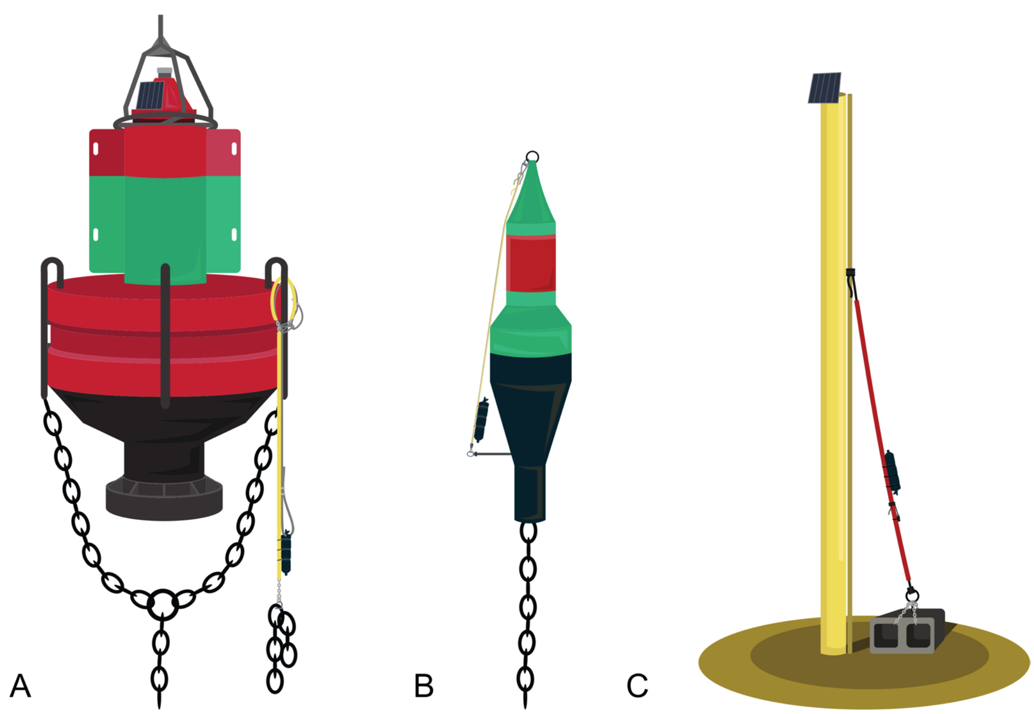

Fig. 2 Receiver attachment designs for the Swimway array and range test arrays. **A** Large buoy attachment with downward-facing receiver. **B** Small buoy (spar) attachment with downward-facing receiver. **C** Fixed pole attachment with upward-facing receiver and range test tag

low and high-power ID codes (147 and 152 dB re 1 μPa at 1 m, respectively) to compare subsequent differences in detection range.

For the large-scale study, each station comprised of a single VR2Tx receiver with a time-logging built-in sync tag transmitting at 69 kHz. Internal sync tags were set to transmit at random intervals between 540 and 660 s. Sync tag transmissions were emitted at a power level referred to by the manufacturer as 'very high', which corresponded to 160 dB re 1 μPa at 1 m (roughly equivalent to the high-power transmissions emitted by Innovasea V16 tags: https://www.innovasea.com/fish-tracking/products/acoustic-transmitters/). Data were collected every 6 months, after which time receivers were redeployed. Due to damage or loss of receivers after the first deployment period, fewer receivers were available during the second deployment period. For the detection range analysis ($N=51$ total stations) this corresponded to 49 stations during the summer period and 31 stations in the winter period, while the analysis of detection efficiency ($N=22$ total stations) incorporated data from 21 stations during the summer and 18 stations during the winter.

Environmental data

At both array scales, a number of environmental datasets were used to determine the potential influence of local environmental conditions on hourly detection efficiency (Tables 2 and 3). For both study scales, details on data sources are provided in Additional file 1.

At the small array scale, investigated factors included water temperature (°C), salinity (PSU), relative water level (m), wind speed (m/sec), wind direction (°), precipitation amount (mm), bottom depth (m NAP), and Topographic Position Index (TPI). To account for the circular periodicity of wind direction, hourly mean wind direction was transformed first into radians and subsequently into the sine and cosine of each value representing directions along the east–west and north–south axes, respectively. These paired predictor variables were then

Table 2 Measured environmental variables for GLMM analysis of detection efficiency in a small-scale range test array ($N=5$ receiver stations)

Data	Measurement location	Units	Mean (SD)	Min	Max	Measurement frequency
Temperature	Jetty	° Celsius	6.9 (0.6)	5.1	8.0	10 min
Salinity	Jetty	PSU	29.4 (1.2)	26.5	31.5	10 min
Relative water level	Den Helder	m	0 (0.5)	− 1.3	1.1	1 h
Wind direction	De Kooy	°	192.8 (72.1)	10	360	1 h
Wind speed	De Kooy	m/s	5.2 (3.2)	1	19	2 h
Precipitation	De Kooy	mm	0.2 (0.5)	0	5.8	3 h
Bottom depth	Per station	m NAP	− 7.6 (6.0)	− 2.3	− 22.3	Single measurement
Topographic position index	Per station	Proportion	− 0.1 (0.3)	− 0.6	0.3	Single measurement

Continuous measurements were recorded by the NIOZ monitoring platform (jetty) in the Marsdiep or by measurement stations of the Royal Netherlands Meteorological Institute (KNMI) in Den Helder and De Kooy. Bathymetric data were made available by Rijkswaterstaat. Data were binned to hourly intervals for comparison to hourly detection efficiency. Data from receiver pairs separated by > 800 m distance were excluded

Table 3 Measured environmental variables for GLMM analysis of detection efficiency in a large-scale range test array ($N=22$ receiver stations)

Data	Measurement location	Units	Mean (SD)	Min	Max	Measurement frequency
Temperature	Per station	° Celsius	12.1 (5.2)	− 0.6	24.5	1 h
Tilt	Per station	°	156.9 (15.9)	15	180	1 h
Ambient noise	Per station	mV	399.1 (161.7)	1	999.9	1 h
Wind direction	De Kooy, Vlieland, Hoorn Terschelling	°	200.1 (99.1)	10	360	1 h
Wind speed	De Kooy, Vlieland, Hoorn Terschelling	m/s	6.3 (3.3)	0	27	1 h
Bottom depth	Per station	m NAP	− 8.8 (5.6)	− 1.7	− 31.4	Single measurement
Relative water level	Per station	m	0 (1)	− 2.8	3.7	1 h
Topographic position index	Per station	Proportion	− 0.1 (0.2)	− 0.6	0.5	Single measurement

Continuous measurements were recorded by VR2Tx acoustic receivers (temperature, tilt, and ambient noise) and by measurement stations of the Royal Netherlands Meteorological Institute (KNMI) at Den Kooy, Vlieland, and Hoorn Terschelling. Water-level measurements and bathymetric data were made available by Rijkswaterstaat. Continuous data were binned to hourly intervals for comparison to hourly detection efficiency. Data from receiver pairs separated by > 800 m distance were excluded analyzed in place of the single metric for wind direction [28, 29]. To account for tidal variation, relative water level was calculated for each station as the hourly mean sea surface height, centered around the overall mean for each station. As an approximation of diurnal variation in biological and anthropogenic noise, for example, resulting from vessel activity in the area, and in particular, frequent crossings of a large passenger ferry through the center of the array, an additional binary factor was used to indicate day *vs.* night. 'Day' was defined as the period between sunrise and sunset (based on times relative to the city of Amsterdam for each day of the study period, obtained via NOAA Solar Calculator: https://gml.noaa.gov/grad/solcalc/), with the remaining hours classified as 'night'. Topographic Position Index was used to indicate the slope of bathymetric features surrounding each receiver station which could reflect or obstruct acoustic signals. This value was calculated using the package *stars* [30] with a chosen kernel size of 7.5 pixels (equivalent to an area of ~ 150 m^2) centered around each receiver station.

On the larger scale, several of these factors were re-examined, with the addition of receiver tilt (°) and ambient noise (mV). In two cases, where bottom depth was either not available or the station's location appeared to correspond to a tidal flat, bottom depth was corrected by extracting the nearest available value at horizontal distances of 355 and 32 m, respectively. Similarly, when precipitation data were absent from one weather station, available values were taken from the next closest weather station. It should be noted that, in the large-scale array, all receivers were deployed with the hydrophone pointing down toward the seabed, and therefore had tilt angles ranging from ~ 150 to 180° upon deployment.

Data analysis

Calculating detection efficiency Detection efficiency refers to the proportion of total transmissions detected by a receiver within a set time period [16]. Due to the random transmission delay of some acoustic tags—such as the range test tags used in our small-scale study—the number of transmissions sent within a given time window varies slightly over time. This creates challenges when attempting to determine the exact time of tag transmissions, necessitating the aggregation of detection data over longer time periods [15]. To address this issue, we aggregated the number of transmissions per hour. For the small-scale study, the expected number of transmissions per hour was defined as the total number of detections recorded for a co-located range test tag during that hour. Co-located tags are defined as those which were deployed on the same station (buoy or pole) as a given receiver and therefore represent a receiver–tag distance of 0 m. In the large-scale study, each receiver recorded the total number of sync tag transmissions it sent per hour throughout the study period. For each hour, the total number of sync transmissions recorded by each receiver was considered the expected number of transmissions for that specific hour and transmission ID. At both array scales, detection efficiency was calculated for all fixed distances (*i.e.*, station pairs) for each hour over the entire study period. Expected detections and detection efficiency were calculated separately for high- and low-power transmissions.

Calculating detection range A common measure of detection range is known as the effective detection range, representing the distance at which, on average, a set percentage of tag transmissions are detected by a receiver [5]. The most commonly reported range is the midpoint range (or D50), which represents the distance at which an average of 50% of transmissions will be detected [12, 16]. To determine the relationship between detection efficiency and distance in each of our arrays, we modeled hourly detection efficiency over the range of available distances using a dose–response model in R (package *'drc'*) [31, 32]. Using mean detection efficiencies recorded at each available distance over the full study period, the relationship between detection efficiency and distance from a tag was modeled using the following dose–response curve [32]:

$$P(Y=1) = \frac{1}{1+\exp(b(\ln(x)-\ln(e)))}.$$

Using the function *ED*, we then predicted the average 50% (midpoint) and 5% ('maximum') detection ranges at both small and large array scales. To capture the full extent of the curve while preventing zero-inflation, data from the large-scale array were filtered to include only receiver–tag distances < 2000 m (51 receiver stations, Fig. 1c). For the small-scale range test, midpoint and maximum detection ranges were also modeled for both high- and low-power tag transmissions. Euclidean distances between receivers and tags were calculated using the *spDist* function as part of package *'sp'* in R [33]. The slopes of the dose–response curve (b) and the effective dose (e) were estimated for both high- and low-power tag transmissions.

Assessing the effects of environmental conditions on detection efficiency To determine the effect of the environment on temporal variation in detection efficiency, we fitted a generalized linear mixed-effects model (GLMM) at each study scale using the package *lme4* in R [34]. These models used 'receiver' as a random effect and included a binary response variable as a proxy for hourly detection efficiency. Specifically, hourly observed detection efficiency was compared to the values predicted for each receiver–tag pair (*i.e.,* distance from tag) from the corresponding dose–response curves (see previous section for model equation). A value of 1 or 0 was then assigned to each study hour based on whether the observed detection efficiency was greater than the model's prediction for that distance and was thereby improved [1] or less than the predicted value and therefore not improved (0). Using this binary value as our new response variable, the effects of both the measured and calculated environmental variables were assessed. To exclude co-located detections (distance 0) and extreme distances with few data points, the model dataset was filtered to exclude values recorded at less than 200 m and greater than the maximum detection range (see Results).

Prior to fitting the small-scale model, salinity was excluded as a predictor due to significant collinearity with temperature (VIF > 3; Fig. S2, Additional file 1). This decision was supported by findings from a similar study conducted in an estuarine environment in Belgium [15]. As in the previous study, temperature was retained due to its presumed greater effect on sound transmission through water relative to salinity (change in speed of sound of 4.0 m/s per 1 °C *vs.* 1.4 m/s per 1 psu) [8]. Additionally, the limited variability in temperature (range: 5.1–8.0 °C) and salinity (range: 26.5–31.5 psu) during the study period was considered (Table 3). The fixed effect describing the method of receiver attachment (buoy, spar, or pole), as depicted in Fig. 2, was also removed in favor of the colinear fixed effect for bottom depth (VIF > 11). The deviance analysis between models with either depth or attachment type, alongside all other variables, showed no significant difference (ΔDeviance = 0.82, $p = 0.82$); however, the model with depth was preferred due to its slightly lower residual deviance. Correlation matrices of factors included at both array scales can be found in Additional file 1 (Figs. S2, S3).

All data analyses were performed using R software [31].

Results

Detection range and efficiency in a small-scale array

In the small-scale array, the predicted probability of improved detection efficiency (hereafter referred to as 'predicted detection efficiency') declined rapidly with increasing distance between receiver–tag pairs ($N = 6$ receivers) (Fig. 3). Specifically, a difference in midpoint detection range of 5.2 m per dB (26 m total) was observed between the low- (147 dB) and high-power (152 dB) transmissions. For low-power transmissions, the midpoint and maximum detection range were estimated to be 123 m and 432 m, respectively (Table 4). Meanwhile, for high-power tag transmissions, the midpoint range was estimated as 149 m with a maximum range of 610 m (Table 4).

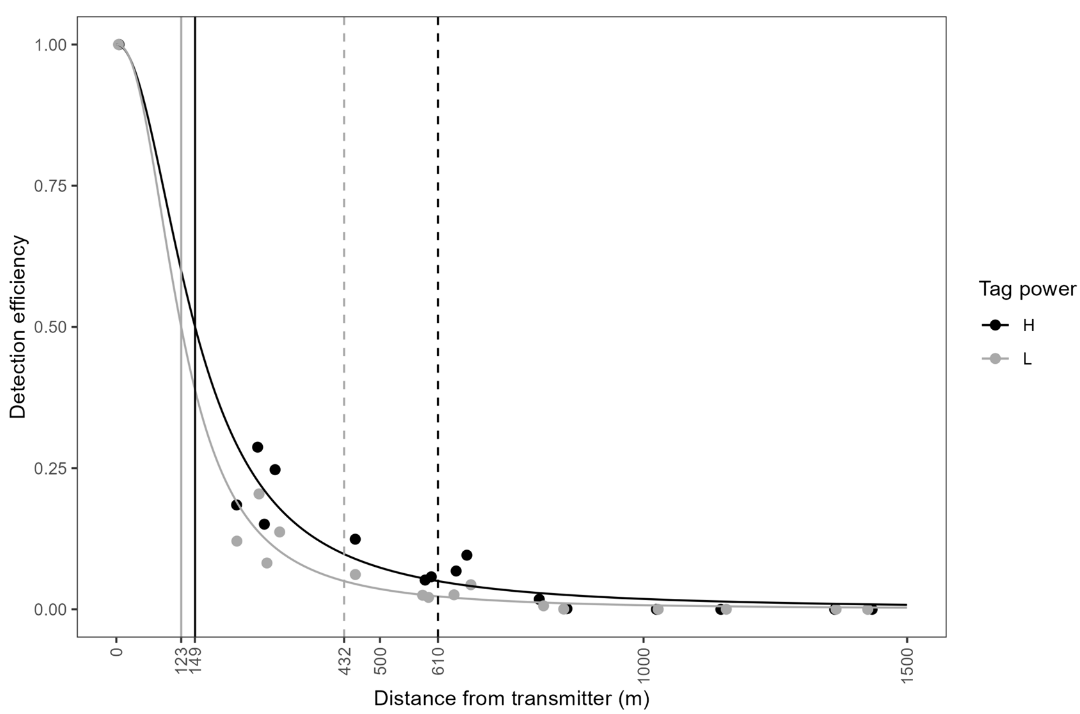

Fig. 3 Dose–response curves and mean detection efficiencies for high (H) and low (L) power tag transmissions at a range of set distances between tag and receiver pairs. Points represent the hourly detection efficiencies of each pair, averaged over a period of 25 d. Midpoint (50%) and maximum (5%) detection ranges are indicated by the solid lines and dashed lines, respectively

Table 4 Estimated midpoint detection ranges for acoustic tag transmissions at high and low tag power levels

Power level	Slope	D50	SE	CI Lower	CI Upper
High	2.1	149.4	6.1	137.4	161.3
Low	2.3	123.1	6.9	109.6	136.6

The estimated dose (D50) represents the distance at which detection efficiency equals 50%

Also shown are the slope of the dose–response curve (*b*), standard error (SE), and the lower and upper limits of the 95% confidence interval for detections recorded at high (152 dB re 1 μPa at 1 m) and low (147 dB re 1 μPa at 1 m) tag power levels.

At distances less than the maximum detection range (610 m), several of the predictor variables, including wind speed, temperature, relative water level, and the interaction between wind speed and north–south wind direction, were found to be highly significant with $p < 0.05$ ($N = 5$ receivers) (Fig. 4, Table 5). Wind speed was the most important environmental factor and had a strong negative influence on variation in predicted detection efficiency. The interactions between wind speed and direction were also significant but varied in their effect strength and direction. Specifically, variations in wind direction along the north–south axis (cosine values) had a strong positive effect, while variations from east to west (sine values) had a slightly weaker, negative effect (Fig. 5a). Water temperature was the second most influential factor, with higher temperatures resulting in increased predicted detection efficiencies. Precipitation amount, bottom depth, Topographic Position Index, and the 'night' period of the binary factor day/night had no significant correlations.

Detection range and efficiency in a large-scale array

For the large-scale array, in which sync tag power was set to 'very high', midpoint, and maximum detection ranges were estimated as 311 m (95% CI 309–313 m, SE = 1.02) and 896 m (95% CI 891–901 m, SE = 2.67), respectively (Fig. 6). A comparison between high-power transmission used in the small-scale study (152 dB; Fig. 3) and these very high-power transmissions (160 dB) shows a difference in midpoint range of more than twofold (149 m for high power *vs.* 311 m for very high power; Fig. 6).

Nearly all of the modeled predictor variables, as well as interaction terms for wind speed and direction, were found to have a significant impact on predicted detection efficiency, with $p < 0.05$ (Fig. 7, Table 6). The majority of the environmental predictors had a negative relationship with predicted detection efficiency, while receiver tilt and water temperature were the only significant factors found to have a positive effect. Wind speed was the most important factor, with a strong negative influence up to

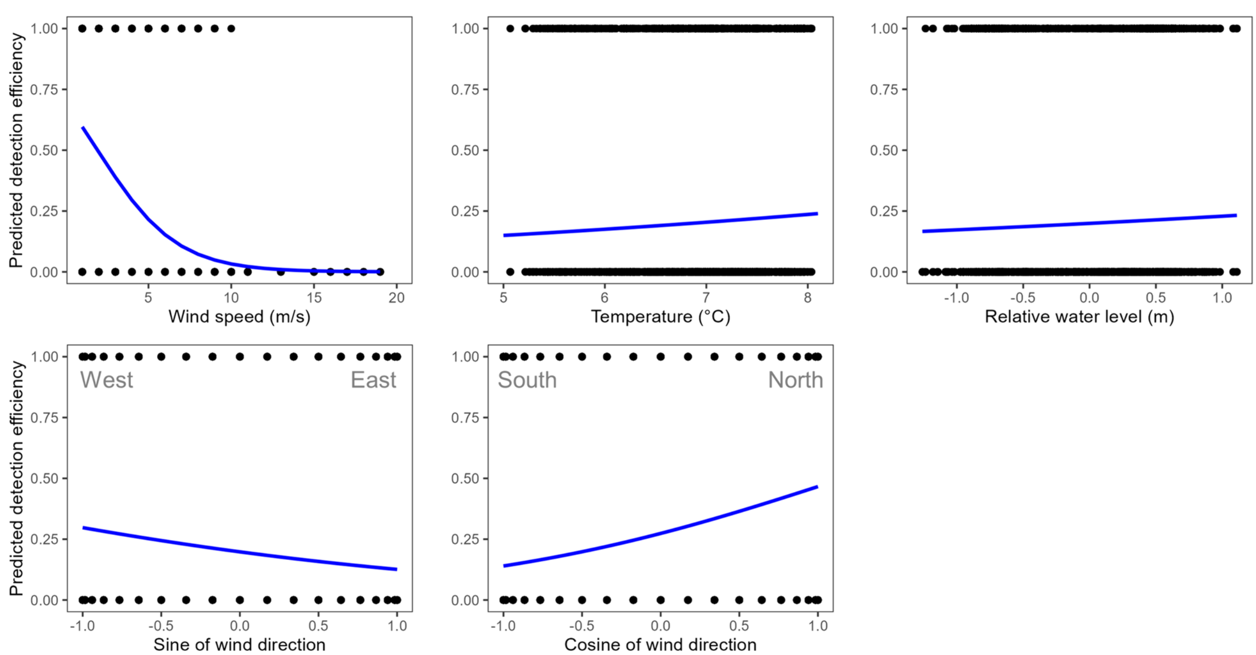

Fig. 4 Predicted probability of improved detection efficiency in a small-scale range test array ($N = 5$ receiver stations). Detection efficiency was predicted in relation to each continuous variable with all other variables held constant at their respective means. Variables displayed are those with significant predictive power ($p < 0.05$), with the addition of the sine and cosine of wind direction, which were significant only when interacting with wind speed

Table 5 GLMM output for potential factors influencing variation in detection efficiency in a small-scale range test ($N = 5$ receiver stations)

Coefficients	Estimate	Std. error	z value	Pr(>|z|)	Signif. Codes
(Intercept)	− 0.425	0.406	− 1.047	0.295	
Wind speed	− 0.356	0.018	− 20.138	< 0.001	***
Wind direction sine (east–west)	0.056	0.097	0.576	0.564	
Wind direction cosine (north–south)	0.057	0.088	0.649	0.517	
Temperature	0.189	0.053	3.533	< 0.001	***
Precipitation	− 0.038	0.061	− 0.615	0.538	
Day/night (night)	0.072	0.062	1.148	0.251	
Bottom depth	0.015	0.016	0.951	0.342	
Relative water level	0.175	0.064	2.746	0.006	**
Topographic position index	− 0.133	0.382	− 0.349	0.727	
Wind speed x Wind direction sine (east–west)	− 0.115	0.025	− 4.693	< 0.001	***
Wind speed x Wind direction cosine (north–south)	0.152	0.021	7.146	< 0.001	***

The coefficient estimates (Estimate), standard error (Std. Error), critical value (z value), *p* value (Pr(>|z|)), and significance codes (Signif. Codes). Significance codes are represented as: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

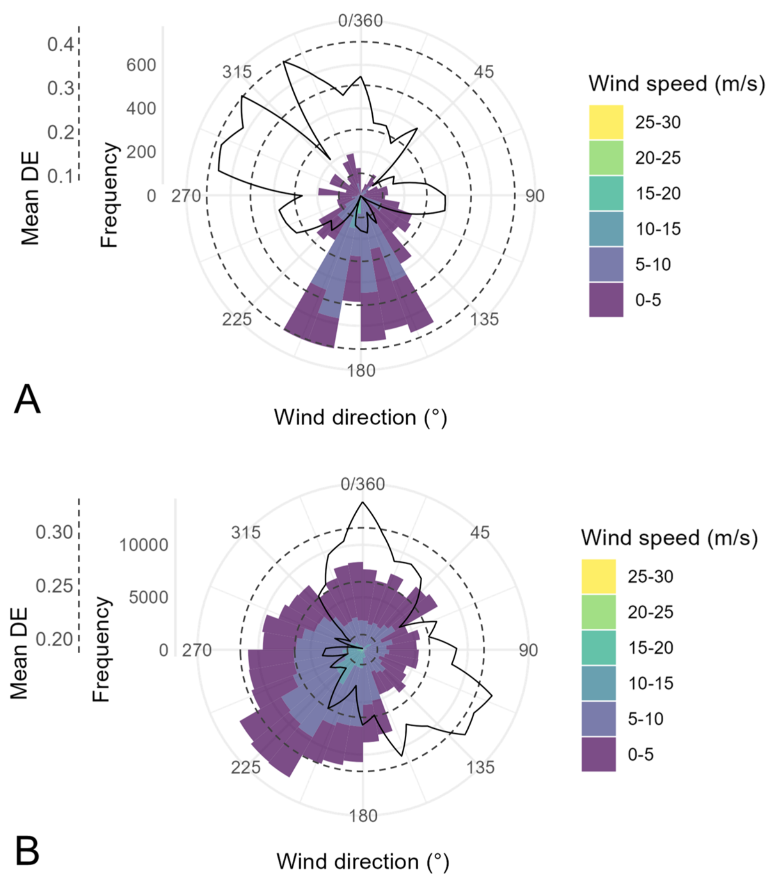

Fig. 5 Variation in measured wind speeds (m/s) and directions (°) and associated fluctuations in mean detection efficiency (DE) recorded in **A** a small-scale range test array ($N = 6$ receiver stations) over a period of 25 d and **B** a large-scale range test array ($N = 22$ receiver stations) over a period of 373 d. Scales refer to concentric circles indicating the value of mean DE (dark dashed lines) and frequency of wind speed and direction (light solid lines)

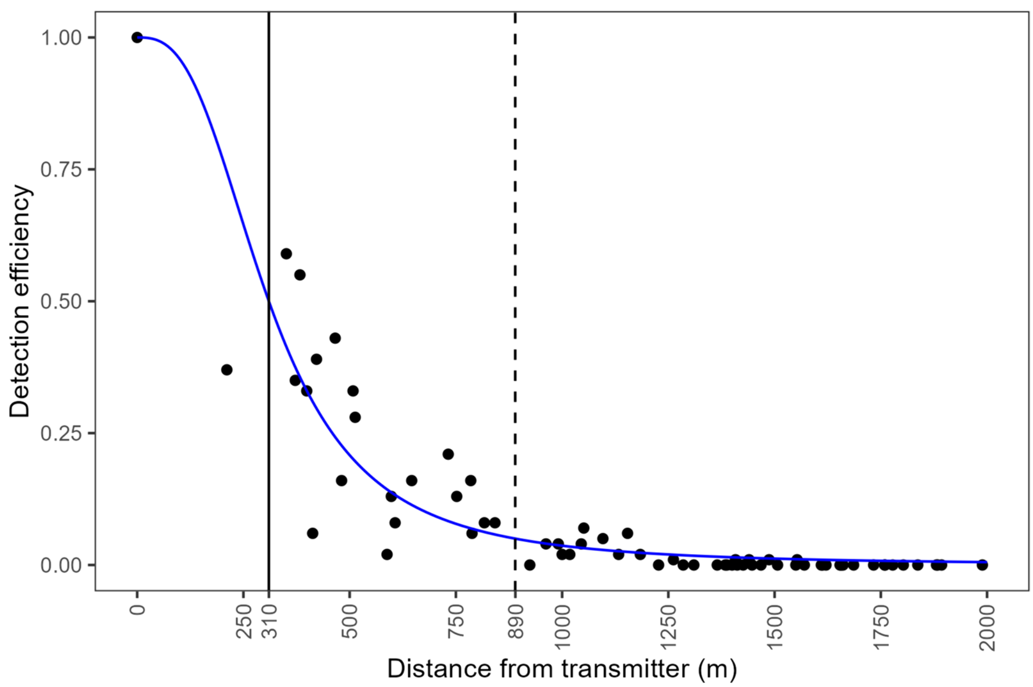

Fig. 6 Dose–response curve and measured detection efficiencies at a range of fixed distances for a large-scale acoustic receiver array in the western Dutch Wadden Sea (N = 51 receiver stations). Points represent the hourly detection efficiencies at each distance, averaged over a period of 383 d. Midpoint (50%) and maximum (5%) detection ranges are indicated by the solid and dashed lines, respectively

speeds of approximately 10 m/s, followed by a plateau of 0% predicted detection efficiency at higher wind speeds (Fig. 7). Wind direction had the strongest influence when variation occurred along the north–south axis, including in its interaction with wind speed (Figs. 5b, 7). The effect of wind direction (both east–west and north–south axes) was most apparent when predictions were compared at various wind speeds (Fig. S4, Supplementary Materials). While bottom depth was not significant, Topographic Position Index also had a strongly negative effect, suggesting increased efficiencies in relation to receiver deployment over concave versus convex bathymetric features (Fig. 7). Results indicated significant effects for both binary fixed effects, receiver attachment type and day/night. Specifically, predicted detection efficiency was reduced for the spar attachment relative to the buoy attachment (see Fig. 2 for attachment details), as well as during the night. Lower predicted detection efficiency was also associated with increases in ambient noise, precipitation, and relative water level, while increased temperature had a strong positive effect (Fig. 7). Receiver tilt had a positive relationship with predicted detection efficiency; however, as receivers are deployed in a downward facing orientation (hydrophone toward the seabed), the tilt of the receiver should be understood as decreasing when there are changes in the receiver angle relative to its natural position (~ 150–180°; see Fig. 2). Decreases in tilt angle thereby represent greater current speeds, which cause the receiver to be pulled toward a horizontal position and suggest an underlying negative relationship between tidal current strength and predicted detection efficiency (Fig. 7).

Discussion

The main objectives of this study were first to quantify average detection range, particularly in terms of tag power output, and second, to evaluate the influence of various environmental conditions on detection efficiency within a coastal marine environment. Through fixed range tests conducted at two array scales, we aimed to emphasize the role of captured environmental variation in shaping range test outcomes.

Detection range and tag power

Controllable features of study design (*e.g.,* equipment selection and programming) work in combination with external influencers to affect array performance. An understanding of their effects can be valuable for the optimization of both research costs (*e.g.,* by reducing the number of receivers required) and tag battery life (*e.g.,* by optimizing tag power and transmission intervals) [17]. For example, our preliminary, small-scale range test revealed significant variations in detection range related to tag power output, guiding decisions on animal tag

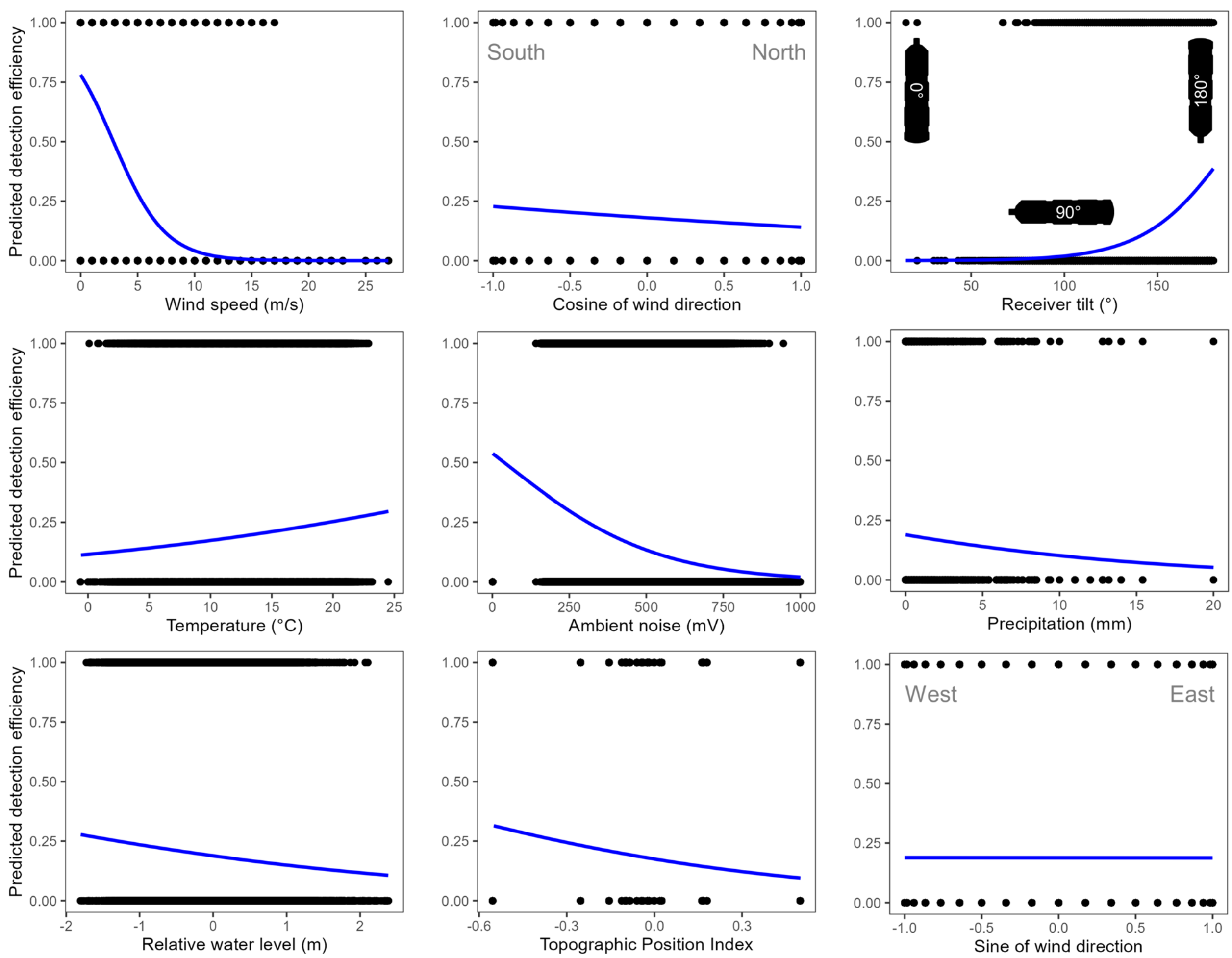

Fig. 7 Predicted probabilities for improved detection efficiency relative to distance from tag recorded in a large-scale range test array ($N = 22$ receiver stations). Receivers were deployed near the surface with the hydrophone oriented toward the sea floor. Detection efficiency was predicted in relation to the displayed set of continuous environmental variables with all other variables held constant at their respective mean values. Variables displayed are those with significant predictive power ($p < 0.05$), with the addition of the sine of wind direction, which was only significant when interacting with wind speed

programming and receiver spacing in our subsequent large-scale array. This increase in detection efficiency with increasing tag power output was also observed in a previous study, conducted across three coastal and offshore study sites in south-western Australia (depth range 9–40 m), that compared the detection profiles of seven acoustic tag types of various sizes and power outputs [35]. Notably, this study reported an immediate decline in detection efficiency for all tag types at the deepest of the three study sites (bottom depth 40 m); however, this result was primarily attributed to the short duration of the local study (7 days) which aligned with a period of unfavorable environmental conditions. These results highlight the importance of local and long-term range test studies to capture variation in environmental conditions occurring over both space (*e.g.*, bottom depth) and time (*e.g.*, meteorological events) [35].

In terms of low-power tags, range tests conducted in the Belgian Part of the North Sea (BPNS) reported a midpoint range of 230 m (148 dB) [18], while results from a nearby estuarine environment in Belgium reported a lower range of 106 m (142 dB) [15]. Although the high-power tags used in the current study (147 dB) had a similar power output to those used in the offshore study, the midpoint range observed in the estuarine environment was more closely comparable to our findings (123 m). Between the two Belgian studies, the discrepancy in midpoint range was thought to result from differences in tag power output (148 *vs.* 142 dB), depth (23 *vs.* 2 m), and ambient noise levels (316 *vs.* 378 mV) [15, 18]. However,

Table 6 GLMM output for potential factors influencing variation in detection efficiency in a large-scale range test (N = 22 receiver stations)

Coefficients:	Estimate	Std. error	z value	Pr(>|z|)	Signif. Codes
(Intercept)	− 0.779	0.312	− 2.495	0.013	*
Wind speed	− 1.435	0.008	− 184.854	< 0.001	***
Wind direction sine (east–west)	− 0.003	0.008	− 0.368	0.713	
Wind direction cosine (north–south)	− 0.294	0.008	− 37.599	< 0.001	***
Tilt	0.688	0.007	96.886	< 0.001	***
Temperature	0.247	0.005	47.327	< 0.001	***
Ambient noise	− 0.654	0.006	− 106.171	< 0.001	***
Precipitation	− 0.036	0.005	− 6.606	< 0.001	***
Day/night (night)	− 0.065	0.010	− 6.613	< 0.001	***
Bottom depth	− 0.132	0.134	− 0.985	0.325	
Relative water level	− 0.178	0.005	− 34.605	< 0.001	***
Topographic position index	− 1.403	0.685	− 2.048	0.041	*
Attachment type (spar)	− 0.761	0.376	− 2.023	0.043	*
Wind speed x Wind direction sine (east–west)	0.099	0.010	9.742	< 0.001	***
Wind speed x Wind direction cosine (north–south)	− 0.214	0.010	− 22.328	< 0.001	***

The coefficient estimates (Estimate), standard error (Std. Error), critical value (z value), *p* value (Pr(>|z|)), and significance codes (Signif. Codes). Significance codes are represented as: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

given the similarity in both observed detection ranges and in environmental conditions (*e.g.,* average bottom depth, tidal variation, and ambient noise levels) between the Belgian estuarine study [15] and our study area (Tables 2 and 3), we suggest that the local environment may play a pivotal role in determining detection range. For accurate estimation of detection range in new study environments, we suggest that both tag power output and environmental conditions should reflect those of planned animal movement studies as closely as possible.

Wind speed and direction

At both study scales, wind speed and direction were important predictors of variation in detection efficiency (Tables 5 and 6). Wind speeds recorded during this study were characteristic of conditions in the southern North Sea and closely reflected values reported by a previous study conducted in this region (0.25–21 m/s) [18]. Wind speeds reached a maximum of 19 m/s in the small-scale array and 27 m/s in the large-scale array (Tables 2 and 3), with predicted detection efficiency dropping dramatically toward 0 as wind speeds approached 10 m/s (Figs. 4 and 7).

In the upper water column, wind can reduce sound propagation through the entrainment of air bubbles that scatter and absorb acoustic signals [6, 7]. Strong winds can also contribute to increased ambient noise levels, likely increasing the rate of signal attenuation [8, 18]. As these negative influences on acoustic signal transmission are likely greater in shallower waters than at depth [5, 12], and given the shallow deployment depth of receivers in this study (≤ 2 m from the sea surface), our results are in line with these expectations. Previous studies also have reported the negative effects of increasing wind speed on detection efficiency [7, 15, 18, 35], with others failing to detect a significant relationship [36, 37] and a single study in which a positive effect was reported [38]. Given the combination of factors affecting air entrainment and ambient noise in aquatic systems [8], as well as the potential influence of parameter selection and data composition in determining model outcomes [15, 39], many factors may be accountable for this variation in study findings.

The relationship between wind speed and direction, as mediated by fetch length, can impact wave height, likely influencing the extent of air bubble entrainment and ambient noise in an aquatic environment. Fetch length is determined by topography; therefore, we can expect this effect to be more significant in fresh and coastal marine habitats where proximity to shore can create both shelter from wind and variations in fetch length across an array area. In contrast, in offshore waters where fetch or wind-driven disturbance is likely to be consistent from all directions, wind direction may be of lesser importance [12]. In our study, the interaction between wind speed and the east–west and north–south wind direction were found to be significant at both small and large scales (Tables 5 and 6). In our large-scale study, detection efficiency was greatest when winds were from the south and west; however, results from our small-scale array indicate a reversal of this directionality (Table 5). This can likely be explained by the location of receivers in each array relative to sheltering landmasses such as the barrier islands and intertidal mudflats in our study area (Fig. 1). Specifically, in the small-scale array, receiver stations were all located within 500 m from the closest shoreline and only one station was deployed over a bottom depth of > 15 m (station R2; Table 1). The location of the small-scale array ensures near complete shelter from both northern and westerly winds, possibly accounting for reductions in detection efficiency resulting from south-easterly winds (Figs. 4 and 5b). Conversely, the less-sheltered positions of the majority of receivers included in the large-scale array (primarily situated in westward-facing tidal inlets) would likely result in the greatest exposure to winds from the north and west, leading to the observed reductions in detection efficiency (Figs. 5c and 7). Receiver stations in the large-scale array ranged from ~ 150 m to 2.5 km from the nearest shoreline, with 86% of all stations ($N = 22$) deployed in locations of < 15 m bottom depth. In shallow, nearshore areas, topographical features affecting fetch and wind-sheltering (*e.g.,* shorelines, islands, and intertidal areas) may be important to consider in terms of array design. In such cases, the placement of receivers in wind-sheltered areas may be useful for maximizing receiver performance.

Tidal variation and bathymetry

Tidal patterns can influence acoustic signal propagation via a number of mechanisms, including changes in water column height—and consequently, the position of fixed receivers and tags in the water column—as well as fluctuations in current speed and direction [5]. As sound propagates through aquatic systems, both the sea's surface and bottom substrate act as boundaries, causing reflection and scattering, as well as acting as sources of reverberation [8, 40]. Water column height can modulate the strength of this effect, for instance leading to more rapid signal attenuation in shallow waters due to repeated encounters with the surface and bottom as the sound propagates along a horizontal plane [41]. Previous studies have reported reduced detection efficiency coinciding with decreases in both receiver deployment depth [42, 43] and water column height [41]. Given the predominantly shallow and strongly intertidal area encompassed by our arrays, we predicted that water level, bottom depth, receiver attachment type, and current-induced changes in receiver tilt would all be of significance in predicting variations in detection efficiency.

Relative water level showed a significant effect on predicted detection efficiency at both array scales; however, the direction of the observed relationship was inconsistent between arrays (Figs. 4 and 7; Tables 5 and 6). At the small scale, higher relative water levels (up to a maximum of 1.1 m) were associated with higher predicted detection efficiencies (Fig. 4, Table 5). Meanwhile, increased water levels at the large scale (ranging up to 3.7 m), correlated with decreases in predicted detection efficiency (Fig. 7, Table 6), contradicting our expectations as per the theoretical predictions. We hypothesize that in this intertidal environment, the observed effect was caused by variations in fetch due to the exposure and submergence of tidal mudflats across the study area. Specifically, as water levels rise and tidal mudflats become submerged, the unobstructed sea surface area expands, potentially leading to increased wave height due to wind. Conversely, the positive effect identified at the small scale could be attributed to several factors, including the absence of nearby intertidal mudflats, the limited range of values recorded during the short-term study (potentially excluding tidal extremes), and the minimal spatial scale of the array, which necessitated using a single time-series for relative water level for all receiver stations. These constraints likely influenced the study's results and should be considered when interpreting the observed effects.

Despite the range of bottom depths encompassed by both arrays (Tables 2 and 3), our models failed to identify a significant effect of bottom depth on detection efficiency at either array scale (Tables 5 and 6). Furthermore, our study design precluded a thorough examination of whether detection efficiency might be affected by the placement of receivers near the sea bottom *vs.* near the sea surface. In the small-scale array, only two receivers were deployed at the surface above relatively deep water (− 14 and − 22 m NAP; Table 2), while the remaining receivers were deployed near the bottom at shallow depths (− 2 to − 7 m NAP). As a result, bottom depth was highly colinear with receiver attachment type, preventing the inclusion of both variables in our model. Despite the even broader range of available depths in the large-scale array (depths ranging from − 1.67 to − 31 m NAP; Table 3), bottom depth was not found to be significant and the use of only surface-mounted receivers prevented further examination of receiver deployment depth.

As emphasized by one study conducted in a Georgian estuary, the entire trajectory of an acoustic signal can also have a significant impact on detection efficiency [41]. This result stems from the interplay between the direction of acoustic signal propagation relative to the locations and depths of both the receiver and tag, alongside the bathymetric features of the study area. Topographic Position Index was used as an indicator for bathymetric features, such as areas of raised seabed or gullies, that could affect the transmission of an acoustic signal from one receiver to another. The positive relationship of Topographic Position Index with predicted detection efficiency in the large-scale array suggests that receivers deployed above concave areas of seabed performed better than those deployed above more convex bathymetric features (Fig. 7). This index is a simplified metric used here to describe a more complex bathymetric landscape in which raised features may have contributed to increased signal attenuation.

Tidal currents can also influence detection efficiency by altering receiver tilt. Receiver orientation is of great importance for detection efficiency as the horizontal detection range is maximized when the receiver is in a vertical position, thereby maximizing the area over which a tagged animal can be detected [44]. In the large-scale study (for which records of receiver tilt were available), receivers were deployed at the surface with the hydrophone pointing down and were either attached in a fixed position to a rope-and-pulley system (Fig. 2b) or suspended in the water column on a weighted chain (Fig. 2a). In each of these scenarios, receivers were subject to changes in tilt as the weighted chain, or the buoy itself, was subjected to drag via tidal currents. Our results support the previous findings, indicating that predicted detection efficiency was greatest when receivers approached a vertical downward position and decreased as receivers became more horizontal (Table 6, Fig. 5), presumably as a result of high-current speeds or turbulence. Our model also suggests that buoys showed improved detection efficiency relative to spars; however, the relative influence of a variety of factors related to attachment type (*e.g.,* receiver tilt, ambient noise, and proximity to bathymetric features) would require further study.

Aside from altering receiver tilt, current speed and direction can have direct effects on sound propagation, resulting in a complex relationship with detection efficiency. Several mechanisms are potentially at play, including the effects of flow orientation on the amplitude of sound transmission [45] and Doppler shifts which have the potential to alter the time intervals between individual pulses in an acoustic tag's signal [13]. While not addressed in this study, the intricate relationship between the dominant current direction and the orientation of acoustic signal transmission is likely important for understanding and identifying diurnal and semidiurnal trends in detection efficiency [13, 17]. Specifically, detection efficiency can be increased at high-current speeds when the flow orientation is opposite to the direction of sound transmission [13].

Temperature

For every 1 °C of change in sea water temperature, the speed of sound is altered by 4 m/s [8]. Theoretically, this should effect the transmission and detection of acoustic signals via reduced signal strengths and increased absorption at lower water temperatures [46]. While this is in line with our results, which showed a positive relationship between detection efficiency and water temperature at both scales (Figs. 4 and 5), the previous studies of receiver performance have had varying results. For example, while receivers deployed in river and lagoon areas of Florida found no significant effect of temperature on detection efficiency [47, 48], several others from a range of study sites have found significant negative effects at increased temperatures and as a result of thermal stratification [12, 13, 35, 38, 49, 50]. In deep waters off southeastern Australia, thermocline depth and gradient were among the most important factors affecting detection efficiency and range [12], presumably due to the deceleration of sounds upon entering colder waters and the refraction of signals by boundary layers [6, 50]. These factors are of particular importance when tags and receivers are located on opposing sides of a thermocline and should have a lesser impact upon stratification breakdown [12, 13, 49].

Ambient noise

As expected, due to interference with acoustic transmissions, increases in ambient noise levels resulted in significant decreases in detection efficiency in our large-scale study (Table 6, Fig. 6). In our study setup, water movement produced by currents, waves, or wind, could have contributed to increased ambient noise levels in the upper water column. Specifically, any of these mechanisms likely caused vibration in the structures used for receiver attachment, including the chain used for the large buoys (Fig. 2a), the rope, and pulley setup (Fig. 2b) in which the upper half of the rope extended above the water's surface. However, many other factors can also contribute to ambient noise levels in aquatic environments (biological, anthropogenic, and abiotic sources) [8], and could have also played a role in our study area. In our small-scale study, which was located directly at the entrance to a ferry harbor, we attempted to use the factor 'day/night' as a proxy for variation in boat engine noise produced by the daily operation of two 130 and 135 m ferries. Despite our predictions, detection efficiency was not reduced during the daytime hours in which the ferries are operational and additional boat traffic may be increased (Table 4). While we do not have any direct records of ambient noise during this time, we must therefore assume that this trend was either produced by other factors operating on a diel cycle or that the ambient noise in our study system was greater at night. Given diel differences in detection efficiency, we advise caution while interpreting potential diel patterns in animal behavior as periods of low detections could reflect reduced efficiency rather than true changes in animal activity [14]. This consideration is essential to avoid misinterpreting behavioral patterns based on detection data.

Lessons learned through range testing

Detection range and efficiency have been studied in a variety of aquatic ecosystems, over different seasons, and with diverse array configurations and programming options [5]. The current study helps to highlight three key lessons emerging as relevant across all range test studies.

First, we demonstrate the importance of range testing for informing strategic study design (*e.g.,* array configuration, receiver attachment, tag transmission frequency, and power output) [35, 51], allowing detection efficiency to be optimized under specific study conditions. For example, based on our comparison of detection range for high- vs. low-power transmissions (Fig. 3), and given the relatively large distances between receivers in our array (Fig. 1), we might select for fish transmitters set to high or very high-power outputs, thereby prioritizing increased detection range over extended battery life in future animal tracking studies. Mooring design and receiver attachment method were also found to significantly impact receiver performance (Table 6), revealing the superior detection efficiencies for receivers attached to large buoys relative to the spar-associated receivers in our array (see Fig. 2 for attachment designs). While we were unable to tease apart the exact mechanisms of this disparity, we suspect that the frequent occurrence of spar-type buoys in areas of high-current strengths and wind exposure may have played a substantial role, potentially along with other aspects such as shadowing by the buoy itself and noise created by attachment materials (ropes, chains, and hardware) which were not accounted for in this study. When designing receiver deployment methods, aspects such as noise production and receiver tilt should be thoroughly considered and controlled to the greatest possible extent. When considering the use of platforms of opportunity such as the poles and navigational buoys used in the current study, the drawbacks of available mooring types (*e.g.,* shadowing, noise production) should be weighed against the benefits of their use for receiver attachment (*e.g.,* spatial arrangements, cost).

Second, we provide further evidence that environmental conditions affecting array performance can vary among aquatic environments and study areas, in some cases, even within a study area (*e.g.,* a single array). For instance, in deep-water environments, the depth and gradient of the thermocline can strongly influence detection range [10, 12], while in shallow, well-mixed waters (as in our study), strong thermal gradients are largely absent. Furthermore, conditions, such as water temperature, flow rates, or bathymetry, can differ greatly among geographic regions and certain ecosystem types (*e.g.,* rivers, lakes, and marine environments) [51]. In our study area, geographic differences in landmasses and exposed mudflats were thought to modulate the effect of wind direction for receivers in the small- vs. large-scale arrays. By expanding our large-scale array to cover a broader area, we also captured a wider range of variation in factors, such as temperature, wind speed, bottom depth, and Topographic Position Index, in turn, altering our interpretation of their importance as predictors of detection efficiency. As it is common to extrapolate from small-scale range tests conducted in only part of an array area, this is an important consideration for future range tests.

Finally, while some factors have a relatively consistent influence on acoustic signal propagation (*e.g.,* refraction, reflection by static objects, and bathymetry), many others can vary widely over time (*e.g.,* wind speed and direction, precipitation, currents, water temperature, stratification, ambient noise levels, etc.) [5, 12, 48, 51]. Understanding the temporal scale of these factors, and the complex interactions between and among them, underscores the specificity of range test results to a particular location, array configuration, and study period. By scaling up our study duration, we capture a more representative range of seasonal conditions and extreme weather events occurring within our study environment. Whenever possible, range tests should aim to include a variety of meteorological conditions or should be repeated during different seasons. In addition, interpretations of animal movement data should consider that periods of extreme conditions could coincide with reduced detection efficiency; therefore, the absence of detections in such periods may not reflect the absence of tagged animals.

Given their reliance on a suite of complex and specific factors, range test outcomes can be difficult to generalize across studies. Nonetheless, insights from previous range tests can guide future study questions and approaches, helping to prioritize potentially relevant parameters for consideration in similar environments.

Conclusions

The significance of insights derived from both preliminary and large-scale range tests has been underrepresented in acoustic telemetry literature. However, these insights are crucial for refining study design and facilitating nuanced data interpretation. By concurrently monitoring detection efficiency and environmental variations, we can better understand patterns in detection data and more accurately interpret the underlying animal movements. This approach not only enriches our understanding of animal detections but also helps to refine study methodologies. Our research advocates for the value of range testing in refining array design and interpreting animal detection data, emphasizing the importance of conducting range tests in situ and at relevant spatial and temporal scales. This contributes to the advancement of acoustic telemetry methodologies for more robust wildlife research.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-024-00378-x.

Additional file 1.

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Author contributions

All authors contributed to the conceptualization of the study, provided criticism for the data analyses, and reviewed and edited the manuscript text. JEE and HVW conducted fieldwork associated with equipment deployment and data collection. JEE and AIB collaborated on the data investigation and analyses and JEE wrote the original draft.

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Availability of data and materials

The datasets generated and/or analyzed during the current study are archived and published in the NIOZ Digital Archiving System.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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