From: Dominika Phillips
To: Hornsea Project Three; KJ Johansson; Kay Sully
Cc: Andrew Guyton; Stuart Livesey
Subject: Hornsea Project Three (UK) Ltd response to Deadline 4 (Part 6)
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D4_HOW03_Appendix 19_Lawson et al 2016.pdf
D4_HOW03_Appendix 20_Masden 2015.pdf
D4_HOW03_Appendix 21_Wade et al 2016.pdf
D4_HOW03_Appendix 22_Desholm 2005.pdf
D4_HOW03_Appendix 23_Welcker et al 2016.pdf
D4_HOW03_Appendix 24_Cook et al 2018.pdf
D4_HOW03_Appendix 25_Parry 2015.pdf

Dear Kay, K-J

Please find attached the 6th instalment of documents.

Best regards,
Dr Dominika Chalder PIEMA
Environment and Consent Manager

[redacted]

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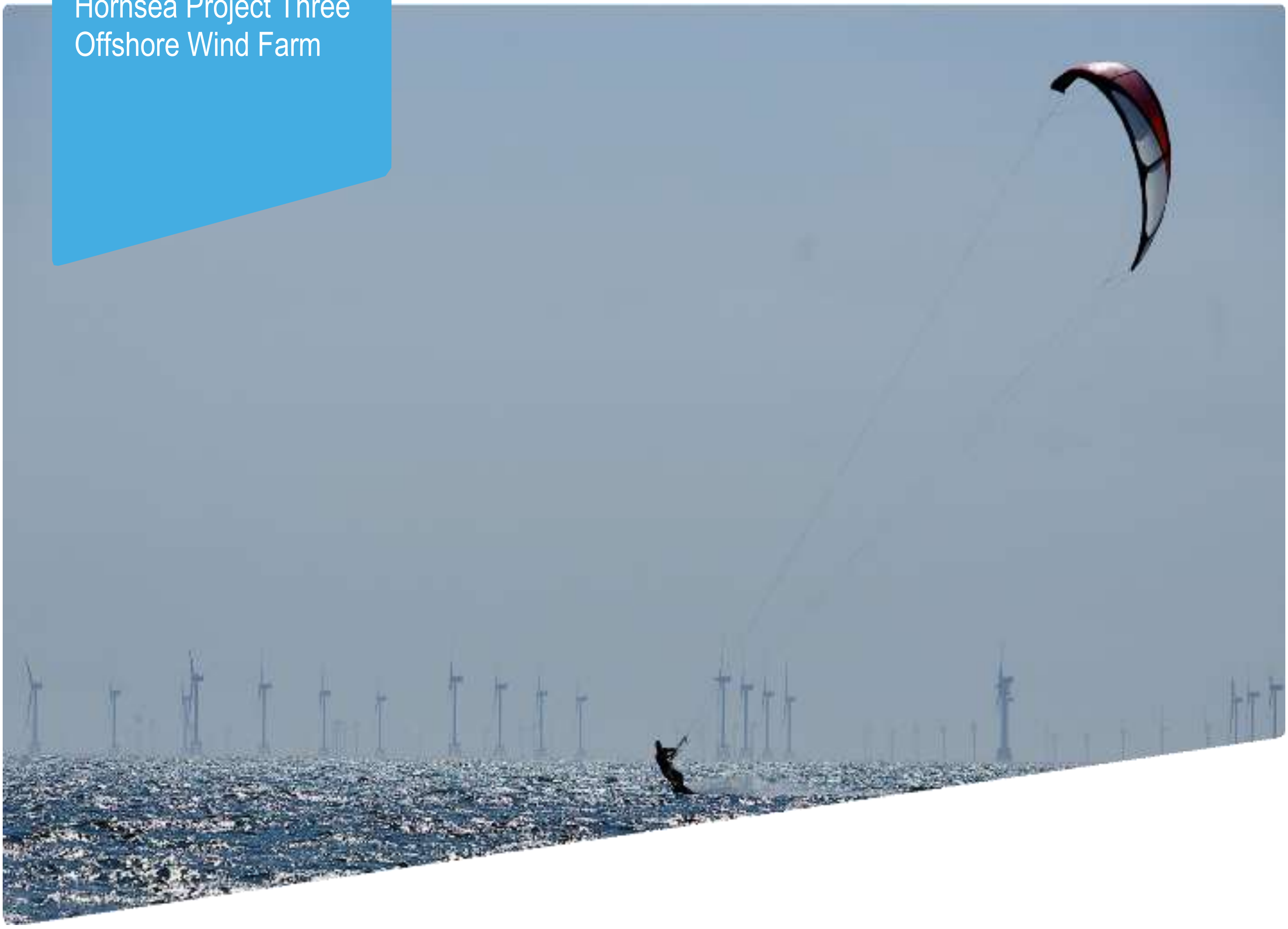
Offshore Wind Farm



Hornsea Project Three

Offshore Wind Farm

Appendix 24 to Deadline 4 Submission – Cook et al., 2018

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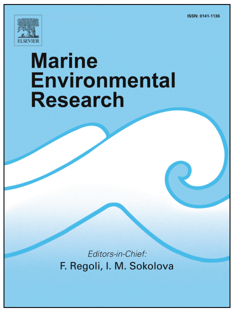
Front cover picture: Kite surfer near a UK offshore wind farm © Ørsted Hornsea Project Three (UK) Ltd., 2019.



Quantifying avian avoidance of offshore wind turbines: Current evidence and key knowledge gaps

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Quantifying avian avoidance of offshore wind turbines: Current evidence and key knowledge gaps

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Abstract

The risk of collision between birds and turbines is seen as one of the key issues in the planning process for offshore wind farms. In some cases, predictions of collision risk have led to projects either being withdrawn from the planning process, or refused planning consent. Despite this, the evidence base on which collision risk is assessed is extremely limited and assessments rely on models which can be highly sensitive to assumptions, notably about bird collision avoidance behaviour. We present a synthesis of the current state of knowledge about collision risk and avoidance behaviour in seabirds. Evidence suggests species-specific responses to turbines and that in order to avoid collision, most birds adjust their flight paths at some distance from the turbines, rather than making last-second adjustments. We highlight the key gaps in knowledge and make recommendations for future data collection.

Keywords

Collision Risk Model, Environmental Impact Assessment, Offshore Wind Farm, Seabirds

1. Introduction

Offshore wind energy is likely to play a key role in efforts to combat climate change through the production of renewable energy (Kaldellis and Zafirakis, 2011). At present the industry is well-developed in northern Europe, and is expanding globally (Breton and Moe, 2009; Snyder and Kaiser, 2009). However, there are concerns over the potential for offshore wind farms to negatively affect wildlife, with impacts on seabirds frequently cited as a key concern (Furness et al., 2013; Garthe and Huppop, 2004).

The main effects of offshore wind farms on seabirds are thought to be: i) collision mortality ; ii) displacement and attraction effects and; iii) barrier effects (Desholm and Kahlert, 2005; Everaert and Stienen, 2007; Masden et al., 2009; Vanermen et al., 2015). Barrier effects occur when the wind farms physically exclude birds causing extended flight journeys around the development during migration or when commuting between colonies and foraging areas (Masden et al., 2010, 2009). Displacement is regarded as a response that results in a functional loss of the habitat available within a wind farm, as opposed to a change in flight trajectory around the wind farm (Drewitt and Langston, 2006; Furness et al., 2013). Whereas attraction to wind farms is argued to be a consequence of turbines serving as a platform for roosting birds or the base acting as a reef resulting in an increase in food availability (Dierschke et al., 2016). Collision mortality describes birds colliding with turbines and associated infrastructure and has received a significant level of attention by the onshore industry as a result of well documented events (de Lucas et al., 2008; Everaert and Stienen, 2007; Loss, 2016; Thaxter et al., 2017a). However, the feasibility of collecting corpses or observing collision events in the marine environment is challenging and, to date, only two studies have reported birds colliding with offshore turbines (Desholm, 2006; Pettersson, 2005).

In the absence of more detailed information about collision rates, Collision Risk Models (CRM) are routinely used to predict the risk posed by offshore wind farms to seabird populations as part of pre-construction Environmental Impact Assessments (EIAS) in Europe (e.g. Ministry of Economic Affairs, 2015; NIRAS, 2015). CRMs are also being used in a range of countries where the offshore wind industry is in the early stages of development including the USA (Cranmer et al., 2017; Fammler and Kuris, 2010; Jenkins et al., 2018; Stumpf et al., 2011). They have also been used in a post-construction context in order to quantify likely collision rates (Skov et al., 2012) and to help estimate the cumulative impact of collisions at multiple offshore wind farms through extrapolation (Brabant et al., 2015; Busch and Garthe, 2017). A variety of different CRMs are available, but at their core most calculate the probability of a bird colliding based on the likelihood of it occupying the same space as a turbine blade. The collision risk to an individual bird is then scaled up based on the number of birds likely to pass through a wind farm over a given time period. The final stage is the application of an avoidance rate which takes into account the proportion of birds likely to take action to avoid a collision (Masden and Cook, 2016). However, outputs from CRMs are known to be sensitive to assumptions made about the avoidance behaviour of the species concerned, notably flight height and flight speed, which are often based on extremely limited data (Chamberlain et al., 2006; Masden, 2015).

Whilst avoidance behaviour can be seen as a continuum over space and time, there is a need to break this down into different components which correspond to how birds may respond to both the wind farm and to individual turbines. Technological limitations associated with measurement have also influenced the definitions but, currently avoidance behaviour is recognised at three different scales (Figure 1), termed macro, meso, and micro (Cook et al., 2014). May (2015) developed a framework for understanding avian avoidance based on the underlying behavioural mechanisms and set out how this related to these three classifications. Macro-avoidance (avoidance of the wind farm as a whole) can arise through a functional habitat loss and is observed as displacement. May (2015) went on to argue that attraction could be included under the term displacement, resulting in what are in effect negative avoidance rates. However macro-avoidance can also include barrier effects, a type of evasive behaviour which can be classified as being impulsive or anticipatory, the latter of which requires early detection or a prior experience or knowledge. Meso-avoidance is the anticipatory or impulsive evasion of rows of turbines within a wind farm. Micro-avoidance reflects the last-second action taken to avoid collision with the turbine blades and may be thought of as an escape response (May, 2015).

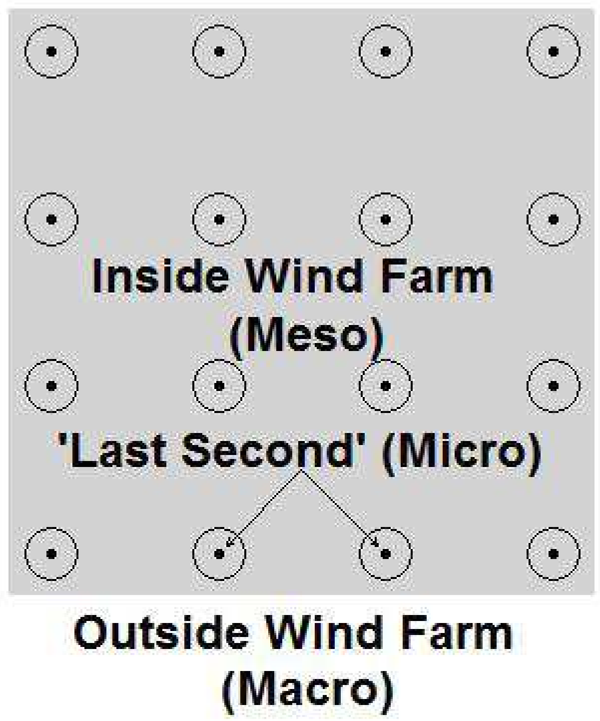

Figure 1 Different scales of avoidance behaviour in relation to an offshore wind farm, turbines indicated by black dots. Macro-avoidance reflects birds either taking action to avoid entering, or birds being attracted to, a wind farm, meso-avoidance reflects birds taking action to avoid individual turbines and micro-avoidance reflects birds taking last-second action to avoid colliding with rotor blades (i.e. within circles surrounding each turbine).

Collisions with turbines may not only have significant conservation implications (Everaert and Stienen, 2007) but important economic consequences as well. In the UK, the Docking Shoal Offshore Wind Farm was refused planning consent over the estimated numbers of Sandwich terns *Thalasseus sandvicensis* predicted to be killed (DECC, 2012), a decision with major implications for both the developer and regulators. Considering the respective economic and conservation concerns, it is vital that decisions about offshore wind farms are made based on the best available evidence. Despite this, there has been no clear agreement about how data describing avoidance behaviour should be collected (Cook et al., 2014; May, 2015). There is a risk that this situation may lead to “decision paralysis” whereby decision-making is constantly postponed whilst additional data are collected (Milner-Gulland and Shea, 2017).

Northern gannet *Morus* bassanus, lesser black-backed gull *Larus fuscus*, herring gull *Larus argentatus*, great black-backed gull *Larus marinus* and black-legged kittiwake *Rissa tridactyla* are viewed as being at a high risk of collision with offshore wind farms due to their flight altitude (Furness et al., 2013; Johnston et al., 2014; Ross-Smith et al., 2016). In northern Europe, the foraging ranges of these species also often overlap with the currently planned offshore wind farm developments (Bradbury et al., 2014; Johnston et al., 2015; Soanes et al., 2013; Thaxter et al., 2015). Here we consider what evidence currently exists to quantify avoidance behaviour for these species. We then describe how these data can be best combined to calculate an overall avoidance rate suitable for use in CRMs for the five key species. In so doing we present an approach which can be adapted for other species and also allows for sufficient flexibility for the inclusion of future data for our example species. Finally, we highlight any gaps in knowledge that we have identified as part of our review.

2. Methods

We focussed our literature search on operational wind farms in northern Europe at which the five key bird species were likely to occur. An online database (www.4coffshore.com) was used to identify offshore wind farm sites, relevant developers and their environmental consultants in order to obtain available reports and data. Web of Science and Google Scholar were used to search for relevant peer-reviewed papers, reports, conference proceedings and book chapters relating to the impacts of wind farms on the five priority species, following literature trails where appropriate. We also referred to previous reviews on the topic (Marine Management Organisation, 2014; Smartwind/Forewind, 2013) to ensure that all sources of primary literature had been identified. Where appropriate, we also considered data relating to the five key species collected from coastal sites, as currently these may reflect the best or only available data on which to base decisions (potential biases are highlighted in section 4.2-Limitations).

2.1 Macro-avoidance

Methodologies which have been used to look at macro-avoidance may not actually distinguish between birds displaced from a wind farm and those exhibiting barrier effects since both can be manifested as a decrease in the numbers of birds in flight within the wind farm area. For the purposes of this review however, we considered studies according to the effect they were designed to investigate. This was not considered an issue as barrier, displacement and attraction effects collectively describe the overall macro-avoidance rate. The key studies included based boat or aerial surveys or from counts from panoramic scans but supporting information was included from GPS tracking studies or radar studies where species identification had been possible. Rates of macro-avoidance were taken directly from the studies cited or calculated using model coefficients (see Cook et al 2014 for more details).

2.2 Meso-avoidance

To assess evidence for meso-avoidance, we considered studies in which the distribution or movement patterns of birds within a wind farm were assessed. Studies selected for inclusion in the review were those which compared the distribution of bird densities or bird movements in the area surrounding individual turbines to the density elsewhere within the wind farm. Surveys were carried out using either visual observations or with radar in combination with visual observations to identify target birds to species level.

2.3 Horizontal vs vertical macro- and meso-avoidance

We considered both macro- and meso-avoidance to have two components, a vertical component and a horizontal component. For the horizontal component, we considered studies in which the distribution of birds (densities) or flightpaths outside the wind farm were compared to the distribution within the wind farm (macro) or with respect to turbines or turbine rows within the wind farm itself (meso).

A significant proportion of birds are likely to fly below rotor-swept height where no turbines are present (Johnston et al., 2014). Consequently, in order to estimate vertical avoidance, a comparison must be made of the proportion of birds at rotor-swept height pre- and post-construction or, inside and outside the wind farm. We searched for studies which met these criteria. These studies were mainly derived from fairly limited visual observations collected from boats or other observation platforms. Data collected using radar were considered, but were found to be at too coarse a scale to be of use.

2.4 Micro-avoidance

Studies of micro-avoidance require detailed behavioural observations of the interaction between birds and turbines due to the fact that they involve last-second escape responses. Therefore, to assess micro-avoidance we considered studies in which interactions between birds and turbines were recorded visually by observers or remotely using radar or turbine-mounted cameras. There was a lack of information which was identified for this scale however.

2.5 Within-wind farm avoidance

Ideally, micro and meso avoidance could be quantified separately for each species in order to generate robust estimates of avoidance behaviour. However, such data may not be available and, given pressures in the decision making process, decisions often rely on the best available data (Milner-Gulland and Shea, 2017). In these circumstances, it is possible to derive avoidance rates by comparing recorded collision rates with estimates of bird flight activity within a wind farm (Band, 2012). As this approach considers all bird movements within a wind farm, it is effectively a combination of both meso-avoidance and micro-avoidance although, it should be noted that it also incorporates elements of bias introduced by estimates of flight activity from the model itself (Band, 2012). We therefore refer to avoidance rates calculated in this way as within-wind farm avoidance. At present, technologies to record collision rates in the offshore environment are still under development (e.g. Collier, Dirksen, and Krijgsveld 2011). Consequently, avoidance rates derived using this approach rely on data from the onshore environment. However, analysis of GPS data indicates that there are likely to be strong differences between flight behaviour on the coast and in marine areas in comparison to the terrestrial environment (Ross-Smith et al., 2016). Consequently, we limited data considered for this analysis to those collected from coastal locations, where flight behaviour may be more similar to that observed offshore, although there may still be some differences (Ross-Smith et al., 2016).

Records of collisions between birds and turbines are frequently reported as a collision rate per year, or a collision rate per turbine per year (Musters et al., 1996). However, in order to estimate a within-wind farm avoidance rate, these data must be combined with estimates of the number of birds passing through the site i.e. the flux rate. We therefore restricted our analyses to sites where estimates of flight activity were also made. Due to likely seasonal and spatial patterns in flight activity, analyses were restricted to sites in which collision and flight activity data were collected during the same months in order to ensure that collision rates reflected seasonal patterns in flight activity data. For these reasons, reported avoidance rates may not match those presented in the original studies. However, we feel it is important that data across sites should be assessed in a consistent way. In order to ensure transparency, Table S3 includes the data and calculations used to estimate the flux rates and within-wind farm avoidance rates at each site. Within-wind farm avoidance rates at each site were estimated using equation 1 (Scottish Natural Heritage, 2010).

$$Within - wind\ farm\ avoidance\ rate = 1 - \left(\frac{Observed\ Collisions}{Probability\ of\ collision \times Flux\ Rate}\right) \qquad \text{Eq. 1}$$

Probability of collision is the likelihood of the blade and bird occupying the same location in space and time based on simplified geometry and is derived using the Band model (Band, 2012), assuming turbine characteristics presented in Table S1 and bird behaviour and morphology presented in Table S2. The probability of collision for each species at each site is given in Table S3. The flux rate is estimated by calculating the number of birds expected to have passed through the wind farm per m^2 per hour scaled up to cover the total turbine frontal area and the total time period during which corpses were collected, and corrected for the proportion of birds at collision risk height and the level of nocturnal activity. The assumptions made during calculations can have a significant impact on the final estimates, and we therefore include Table S3 in supplementary information which shows the step by step process by which we estimated each within wind farm avoidance rate. We then used ratio estimators (Cochran, 1977) to combine avoidance rates across multiple sites and the delta method (Powell, 2007) to estimate the standard deviation associated with the derived avoidance rates.

2.6 Derivation of recommended total avoidance rates

Collision risk estimates are typically based on pre-construction estimates of the total number of birds within a wind farm (Cook et al., 2014). Consequently, the avoidance rates used in collision risk models must account for changes in the total number of birds within the wind farm between the pre- and post-construction periods as well as any redistribution arising from behavioural responses to turbines within the wind farm. The total avoidance rate can then be estimated by combining the macro-, meso- and micro-avoidance rates as shown in equation 2 (Cook et al., 2014; Krijgsveld et al., 2011), or the macro- and within wind farm-avoidance rates as shown in equation 3 (adapted from Equation 2).

$$(1 - \text{Total Avoidance Rate}) = (1 - \text{Macro-Avoidance}) \times (1 - \text{Meso-Avoidance}) \times (1 - \text{Micro-Avoidance}) \quad \text{(Eq. 2)}$$

$$(1 - \text{Total Avoidance Rate}) = (1 - \text{Macro-Avoidance}) \times (1 - \text{Within-wind farm avoidance}) \quad \text{(Eq. 3)}$$

Equations 2 and 3 can accommodate situations where birds are attracted at a macro- or meso-scale. Within these formulae, a value of 1 relates to total avoidance, a value of 0 relates to neither avoidance nor attraction and values less than 0 relate to attraction (i.e. -0.1 would relate to a 10% increase), meaning the avoidance rate is reduced when birds are attracted to the wind farm or individual turbines.

3. Results

3.1 Macro-avoidance – barrier effects

Overall there was limited evidence of macro-avoidance as an apparent consequence of barrier effects for the five priority species (Table 1). Systematic panoramic scans of densities of birds in flight within and around the Egmond aan Zee wind farm in the Netherlands revealed a macro-avoidance rate of 0.64 for northern gannet (n=81) and 0.18 for gull spp combined (Krijgsveld et al., 2011). Using a combination of radar and laser range finders at Horns Rev, a macro-avoidance rate of 0.84 was calculated based on the numbers of tracks of migrating gannets (n=74) which did not enter the wind farm (Skov et al., 2012). The same study also reported an avoidance rate of 0.56 for large gulls (n=84) and 0.69 for kittiwakes (n=11). An earlier study at the same wind farm reported that out of 126 tracks representing 268 individual migrating gannets, none of these entered the wind farm. For migrating gulls (herring, great black-backed, little and kittiwake, 442 tracks out of a total of 461 did not enter the wind farm — although as neither species or size of flock were reported, the avoidance rate cannot be estimated (Petersen et al., 2006). However, in these studies data were collected during the post-construction period only and caution should therefore be applied when interpreting their significance in the absence of pre-development data. Furthermore, data collection also tended to be focused on outside the breeding season and the extent to which this information is relevant to birds when they are tied to their colonies is unclear.

3.2. Macro-avoidance – displacement

From studies of displacement, macro-avoidance was estimated for northern gannet using ship based surveys at the Blighbank wind farm in Belgium (Vanermen et al., 2015) – a rate of 0.85 (Table 1) – and at the Alpha Ventus wind farm in Germany – a rate of 0.92 –although this study was based in an area where gannets densities were low (Welcker and Nehls, 2016). As before, whether these data are representative of behaviour during the breeding season is uncertain as the majority of the data were from the non-breeding season(Vanermen et al., 2013). Of the remaining studies, one reported displacement at two wind farms (Leopold et al., 2013) and another three reported no response of northern gannet, possibly as a result of low densities of birds being present pre- and post-construction (Mendel et al., 2014; Natural Power, 2014; Petersen et al., 2006). An aerial based survey at Greater Gabbard in the UK estimated an avoidance rate of 0.95 (APEM 2014) during the autumn passage period and based on the post construction period only. An additional study of three GPS-tagged northern gannets also indicated that they avoided entering wind farms (Garthe et al., 2017).

One study reported great black-backed gulls as being attracted to offshore wind farms (Welcker and Nehls, 2016), whilst the others reported no response (i.e. no attraction to or displacement from). For lesser black-backed gulls the evidence for macro-avoidance was equivocal with studies reporting attraction, displacement and no response to the wind farms. A recent study of GPS-tagged lesser black-backed gulls suggests that while individuals may differ in their response to offshore wind farms, overall the species did not consistently exhibit displacement or attraction (Thaxter, Ross-Smith, et al. 2017). Herring gull largely showed no response to wind farms with the notable exception at Blighbank and Alpha Ventus where attraction effects were reported (Vanermen et al., 2015; Welcker and Nehls, 2016) possibly linked to increased roosting opportunities provided by the wind farm (the same effect was observed for lesser black-backed gulls at the same site). Black-legged kittiwake showed both displacement effects and no response to wind farms.

3.3. Macro-avoidance – combining all effects

For the species considered in this review, there was evidence that northern gannet exhibit macro avoidance. At this stage, we believe the lower of the available values, 0.64 (Krijgsveld et al., 2011), is an appropriate macro-avoidance rate for northern gannet. This is based on a precautionary approach given that estimates were often based on small sample sizes leading to limited power to detect change combined with most data being collected outside the breeding season. In contrast, based on the studies we identified, none of the gull species appear to show a consistent response to wind farms. In the absence of consistent evidence, we are unable to recommend a suitable macro-avoidance rate for gulls.

3.3. Horizontal meso-avoidance

Meso-avoidance is likely to reflect the anticipatory or impulsive evasion of individual turbines. We identified four studies in which the distribution of birds or flight paths within a wind farm were quantified. Using radar, Krijgsveld *et al.* (2011) and Skov *et al.* (2012) found strong evidence of horizontal meso-avoidance of individual turbines. Krijgsveld *et al.* (2011) reported that the density of birds within 50m of a turbine was 66% of the density elsewhere in the wind farm. Assuming that, in the absence of turbines, birds would be expected to be evenly distributed across the area of the wind farm, this reflects a meso-avoidance rate of 0.34. It is likely that this figure reflects an underestimate of total meso-avoidance as it is based on data collected using horizontal radar and will, therefore, include birds flying above or below the turbines thus not at risk of collision. Skov *et al.* (2012) found a stronger response, with none of the 408 large gulls they recorded passing within 50m of a turbine. However, the primary purpose of this analysis was to collect information describing species flight heights rather than their proximity to turbines. Tracks from radar suggested some birds may approach the turbines more closely. Using visual observations, Janoska (2012) recorded only 23 out of 917 gulls passing within 75m of a turbine, reflecting a meso-avoidance rate of 0.975. By contrast, also using visual observations, Everaert (2008) reported no significant difference in the number of gulls passing within 100m of a turbine (or its proposed site) between pre- and post-construction periods, possibly reflecting the location of the site on a flight line between a roost and a foraging/loafing area. These studies suggest that gulls may have a strong horizontal meso-avoidance of turbines, but that this may be site or context specific. Whilst the data in the studies described above are informative, it should be noted that they are not sufficiently robust to allow firm conclusions to be drawn about the likely magnitude of any meso-avoidance.

In addition to the studies described above, several studies reported anecdotal evidence describing how the relative location of the turbines may influence the distribution of birds within a wind farm. Petersen *et al.* (2006) provided evidence to suggest that birds may be more likely to respond to turbines as the number of turbine rows they passed increased, suggesting stronger avoidance towards the middle of the wind farm than at the edge. Similarly, Winkelman (1992) noted that there were fewer collision victims towards the centre of a wind farm. These data suggest that the strength of any horizontal meso-avoidance may vary with distance from the wind farm centre. There was also evidence from three sites – Horns Rev, Alpha Ventus and Egmond aan Zee – to suggest that birds respond to the operational status of turbines, with higher densities recorded when turbines were not operational, although this effect may be more noticeable at night (Krijgsveld et al., 2011; Mendel et al., 2014; Petersen et al., 2006; Schulz et al., 2014).

3.4 Vertical meso-avoidance

We identified three sites at which the proportions of birds of different species at rotor-swept height could be compared pre- and post-construction – Barrow (Barrow Offshore Wind Limited, n.d.), Gunfleet Sands (GoBe Consultants Ltd., 2012; NIRAS Consulting, 2011) and Robin Rigg (Natural Power, 2013) – and a fourth – Egmond aan Zee (Krijgsveld et al., 2011) – where flight heights were compared inside and outside a wind farm (Table 2). Across these sites, there was no consistent pattern indicating an increase or decrease in the proportion of birds at rotor-swept height in response to the presence of a turbine. However, given the extremely limited evidence, no firm conclusions can be drawn about the extent or direction of any vertical meso-response in any species of marine birds. Furthermore, where flight heights are estimated by observers by eye, it should be noted that any comparison may be confounded by the fact that heights are easier to estimate once turbines have been installed as they offer fixed reference points of known height.

3.5. Micro-avoidance

Micro-avoidance reflects a last second action to avoid collision and, may be thought of as an escape response (May, 2015). We identified 17 sites at which visual observations of the interactions between birds and turbines had been reported (Table 3). Over the course of these studies, only two collision events were directly observed, the first involving a flock of four common eider *Somateria mollisima* at a single turbine at the Utgrunden Offshore Wind Farm in Sweden and the second, a passerine or bat at Nysted Offshore Wind Farm in Denmark (Desholm, 2006; Pettersson, 2005). Whilst it should be noted that collisions may have occurred between observation periods, the number of birds observed interacting with turbines without colliding suggests that collisions are likely to be rare events (Table 3).

Of the studies we identified, only six provided sufficiently detailed descriptions of birds' interactions with wind turbines to characterise micro-avoidance (Table 3; Desholm 2005; Krijgsveld et al. 2011; RPS 2011; Schulz et al. 2014; Thaxter, Ross-Smith, et al. 2017; Wild Frontier Ecology 2013), although these reflected significant effort across multiple sites. Despite this effort, there were very few records of birds flying close enough to turbines to require micro-avoidance. Indeed, Desholm (2005) did not record any birds passing within 20m of a turbine. Similarly, a detailed analysis of two GPS-tagged Lesser Black-backed Gulls indicated that these birds significantly avoided entering the turbine rotor-swept area (Thaxter, Ross-Smith, et al. 2017). Across the remaining studies only 59 birds were recorded as passing close to the turbine rotor-swept area, of which 54 were recorded as taking action to avoid the rotor-swept area (Table 3). The data for micro-avoidance would appear to be consistent with those reported above for meso-avoidance, suggesting that a last second escape reflex may be required relatively rarely as, within a wind farm, avoidance behaviour is driven by a high level of anticipatory or impulsive evasion. However, given the differences in the species recorded interacting with turbines and the relatively low number of birds recorded, it is difficult to draw firm conclusions about the extent of micro-avoidance behaviour.

3.6. Within-wind farm avoidance

We identified nine coastal sites (Table 3) from which data describing the recorded number of collisions were available from the same time periods as estimates of the total number of birds passing through turbine rotor-swept areas. Based on the data presented in the studies highlighted in Table 3, it was possible to calculate species-specific within-wind farm avoidance rates for herring gull and lesser black-backed gull, as well as rates for small gulls (e.g. black-legged kittiwake), large gulls (e.g. great black-backed gull) and all gulls (Table 4) but not for northern gannet.

These analyses confirmed that within-wind farm avoidance rates were likely to be very high (> 0.99) (Table 4). Avoidance rates were similar between species with rates of 0.9959 for herring gull and 0.9982 for lesser black-backed gull. We also estimated group-specific avoidance rates of 0.9921 for small gulls (birds identified as little, common or black-headed gulls), 0.9956 for large gulls (those identified as lesser black-backed, herring or great black-backed gull or described as large gull spp.) and 0.9893 for all gulls (those identified to species level or described as large gull, small gull or gull spp.).

Whilst the level of precision expressed by these values may seem excessive, it should be noted that it is the non-avoidance rate (1-avoidance) which is incorporated in the collision risk model. When presented to four decimal places, the non-avoidance rates typically had 2 significant figures (table 4), which we feel reflects a reasonable level of precision. The difference between an avoidance rate of 0.995 and 0.9959 would result in an 18% increase in the collision rate predicted from the CRM. We would also argue that this level of precision is justified given the estimated level of uncertainty surrounding each value (Table 4).

3.7. Recommended total avoidance rates

Evidence suggests that the response of gulls to turbines at a macro scale may be highly variable. Consequently, at present, we consider all gull species (including kittiwake) to have an average macro-avoidance rate of zero. Few studies were available with which to draw conclusions about meso- and micro-avoidance in gulls. Consequently, the total avoidance rates for gulls can be considered to be equal to the within-wind farm avoidance rates. However, the evidence base for macro-avoidance in gulls was limited meaning it was not possible to produce robust estimates of uncertainty surrounding macro-avoidance rates. Therefore, when combining macro- and within-wind farm avoidance rates, we are not able to give an estimate of uncertainty surrounding the total avoidance rate. Additionally, given the limited evidence base for macro-avoidance, we present the total avoidance rate to three, rather than four, significant figures and round down in order to be precautionary. We recommend total avoidance rates of 0.998 for lesser black-backed gull and 0.995 for herring gull. Based on flight behaviour and morphology, we believe it is reasonable to include the great black-backed gull in the large gull spp. grouping, and the black-legged kittiwake in the small gull spp. grouping. We therefore recommend total avoidance rates of 0.995 and 0.992 respectively for these species.

Fewer data were available to support a total avoidance rate for northern gannet. However, given the evidence of strong macro-avoidance of wind farms, it was felt that the total avoidance rate was unlikely to be below that obtained for all gulls. Consequently, a rate of 0.989 is recommended for northern gannet.

4. Discussion

May (2015) suggests that alertness is likely to increase with decreasing distance to turbines, meaning birds are more likely to take action as they get closer to a turbine. We believe our review supports this hypothesis as, despite significant survey effort, we uncovered very little evidence of birds approaching turbines close enough to be at risk of collision. Of those that did, a high proportion were recorded taking last-second action to avoid collision, termed an escape response by May (2015). In a behavioural context, this suggests that most avoidance action is likely to be caused by functional habitat loss or anticipatory or impulsive evasion, rather than a last second escape reflex. There was also evidence to suggest that the avoidance rate may vary in relation to both the position of a turbine in an array and whether or not turbines are operational (Krijgsveld et al., 2011; Mendel et al., 2014; Petersen et al., 2006; Schulz et al., 2014; Winkelman, 1992), a conclusion consistent with the predictions made by May (2015). Such responses highlight the ability of some species, particularly gulls, to adapt to the presence of wind turbines.

4.1. Use of avoidance rates in collision risk models

Previous guidance of the use of avoidance rates in CRMs was that 0.98 should be considered the default value for seabirds (Scottish Natural Heritage, 2010). Whilst significant gaps in knowledge remain, this review highlights that, for the species most likely to be affected by collision, avoidance rates are estimated to exceed 0.99. Whilst this may seem a trivial difference, it will result in the predicted collision rate being more than halved. These avoidance rates are applicable to models such as Band (2012), as well as others including the models of Tucker (1996) and Eichhorn (2012). However, care must be taken when using these avoidance rates in models which account for the vertical distribution of birds when estimating the probability of collision (e.g. the Extended Band Model Band, 2012). Accounting for the vertical distribution of birds will reduce the number of collisions predicted in the absence of avoidance as the number of birds within the central, and more risky part of the rotor-swept area will be reduced (Johnston et al., 2014). Consequently, within-wind farm avoidance rates suitable for use with models such as the extended Band model (Band, 2012), which do account for vertical distribution, are likely to be lower than those suitable for use with simpler models. At present, insufficient data are available with which to estimate robust avoidance rates for use in the extended Band model for most species. However, with ongoing data collection in the offshore environment, for example through the UK Offshore Renewables Joint Industry Project (Davies et al., 2013), it is to be hoped that this review will help inform for the collection of appropriate data in future.

4.2. Limitations

At present, our recommended avoidance rates only consider horizontal avoidance. We identified some evidence suggesting birds may alter their flight altitudes when within a wind farm in order to reduce collision risk (Table 2). However, this evidence was inconclusive and further studies are required in order to fully understand vertical avoidance behaviour. Technological advancements, for example, the availability of radar (Kunz et al., 2007; Skov et al., 2016; Ward et al., 2016) and GPS tags (Corman and Garthe 2014; Garthe et al. 2017; Thaxter, Ross-Smith, et al. 2017) which can collect detailed information about the movement patterns of individual birds may mean these data could be collected in the near future. Combining horizontal and vertical avoidance rates in order to derive a three-dimensional avoidance rate is unlikely to be straightforward as birds may employ both strategies at the same time, meaning simple formulae like equation 2 are unlikely to be appropriate. However, approaches such as that used with GPS tracking data by Thaxter *et al.* (2017) may prove valuable.

Within wind farms (i.e. at meso- and micro-scales) a lack of data from the offshore environment is an issue, particularly in relation to northern gannet. Whilst data from terrestrial sites are informative about how birds may interact with individual turbines, evidence suggests that flight behaviour may differ between onshore and offshore environments (Corman and Garthe, 2014; Ross-Smith et al., 2016) potentially affecting how birds respond to turbines and therefore avoidance rates. Whilst we have attempted to minimise the impact of this by focussing on data collected from coastal locations, some differences may remain, notably in relation to flight height and speed (Corman and Garthe, 2014; Ross-Smith et al., 2016; Spear and Ainley, 2008). Birds tend to fly higher over land than offshore and, there is also a greater tendency for them to fly at altitudes within the rotor-swept area of turbines in the terrestrial environment (Corman and Garthe, 2014; Ross-Smith et al., 2016). This greater potential exposure to turbine blades means that collision rates in the terrestrial environment may be greater than is the case offshore. Seabird flight speed can be strongly influenced by weather conditions, particularly wind strength and direction (Shamoun-Baranes and van Loon, 2006; Spear and Ainley, 2008), potentially affecting their manoeuvrability and ability to respond to obstacles. As wind conditions can differ markedly between the onshore and offshore environments, this is likely to have implications for collision risk. However, at present insufficient data are available to enable us to understand in which direction this may influence collision risk.

The within-wind farm avoidance rates presented here are higher than those derived by Everaert (2014). This may partly reflect the broader range of sites covered by our review, especially as some of the sites covered in Everaert (2014) appear to have particularly high collision rates. In particular Everaert (2014) highlights the proximity of one wind farm to a breeding colony as a key reason for a high collision rate. This highlights the importance of considering site-specific variation in avoidance behaviour, which we have attempted to capture by estimating confidence intervals around our within-wind farm avoidance rates. However, even when we estimate within-wind farm avoidance rates from similar data, the values derived as part of our review differ from those presented by Everaert (2014) (Table S3). A key reason for this is that, in order to ensure data were consistent with those collected elsewhere, we have only considered data where no spatial or temporal extrapolation was required in order to combine collision and flight activity data. We recognise that there are a number of ways in which avoidance rates can be derived, and that small differences in the way some parameters are derived (i.e. passage rate), and biases due to survey technique, can strongly influence the final estimated avoidance rates. This is undesirable as it can increase uncertainty in the consenting process, increasing costs for those involved. For this reason, we strongly suggest that authors provide detailed calculations showing how the rates presented have been estimated in order to enable readers to come to an informed decision about the results (see Table S3).

To date, there has been little consideration of factors which are likely to influence avoidance behaviour and to what extent there is seasonal- or site-specific variation in the offshore context. Avoidance rates for non-seabird species at onshore wind farms have been reported to vary by site and even within wind farms (Garvin et al., 2011), as well as by season, whether birds are resident or migrants and the relative distance to the wind farm from roost sites or nest locations (Campedelli et al., 2014). It is apparent, therefore, that the magnitude of any avoidance behaviour is likely to be linked to the ecological importance of a site to a species at a given point in time, and how it is being used. Seabirds act as central place foragers during breeding (Stephens and Krebs, 1986; Thaxter et al., 2012). This may manifest itself in spatial differences in behaviour, dependent upon whether the area covered by an offshore wind farm is used for active foraging or for commuting between foraging grounds and the breeding colony. Such behavioural differences may be associated with varying levels of collision risk and avoidance behaviour. There may also be a temporal element to avoidance behaviour. Stage-dependent changes in foraging behaviour between the incubation and early chick-rearing period have explained the change in spatial overlap with offshore wind farms (Thaxter et al., 2015). The presence of newly fledged birds in the population towards the end of the breeding season may also affect avoidance rates as these naive individuals may unintentionally engage in riskier flight behaviour (Henderson et al., 1996). Individual seabirds may also show consistency in their preferred foraging areas (Irons, 1998; Soanes et al., 2013) or have limited alternative habitats available. Where wind farms overlap with these preferred foraging areas, displacement may be less likely and macro-avoidance rates therefore lower for these individuals. These studies suggest that there are likely to be both spatial and temporal elements to avoidance behaviour for seabirds, neither of which have yet been properly quantified. There is also some evidence to suggest that group size and social interactions can influence the likelihood of collision and hence by association, the avoidance behaviour of birds (Croft et al., 2013). Other factors which influence collision risk have also been reviewed extensively (Marques et al. 2014; May et al. 2015; Thaxter, Buchanan, et al. 2017; Wang et al. 2015) and include aspects of: species characteristics (morphology, flight behaviour, sensory perception, phenology); site features (landscape, food availability, weather); and wind farm features (type of turbines and design of array).

4.3. Future data collection — displacement and functional habitat loss

Whilst this study has advanced our understanding of avoidance behaviour of seabirds in relation to offshore wind farms, a number of significant gaps in knowledge remain. Collecting the data necessary to quantify avoidance behaviour in relation to offshore wind farms can be extremely costly and therefore requires well designed studies involving both industry and regulators (e.g.

Davies et al. 2013). The cost and challenging nature of these studies means that it is important to utilise robust analytical approaches that make the most of any data collected.

Studies of displacement/attraction have typically used Before-After-Control-Impact (BACI) survey design (Stewart-Oaten et al., 1986) but have been hampered by inadequate survey design notably gaps in spatial or temporal coverage and inappropriate choice of control sites (Marine Management Organisation, 2014). Recently developed approaches, such as Before-After-Gradient (BAG) analyses are increasingly used to assess the impacts of wind farms with the focus on collecting data over much more extensive areas around the wind farm site starting in the pre-construction period (Jackson and Whitfield, 2011; Mackenzie et al., 2013; Marine Management Organisation, 2014; May, 2015). By incorporating environmental covariates (e.g. sea surface temperature, tidal cycles) to help describe spatial and temporal variation in seabird distributions and abundance at sea, further changes associated with the construction and operation of wind farms can be more accurately attributed (Mackenzie et al., 2013), and therefore better inform macro-avoidance rates. Species assumed to be at risk of displacement (Furness et al., 2013), tend to have estimates of avoidance based largely on data collected at the macro-scale. In the case of species for which displacement is not perceived to be a significant issue, for example gulls, there is often less focus on data collection at this scale, meaning the macro level response to wind farms is often less well understood. By focussing data collection on the scale perceived to be most relevant for the species concerned, there is a risk that avoidance behaviour at other spatial scales is overlooked. Whilst this is primarily an issue for data collected using observational surveys, it may also be an issue for data collected using radar depending on the range over which the system operates.

To help to provide a better evidence base for macro-avoidance, future analyses should distinguish between birds in flight and those on the water, as only those in flight are at risk of collision. Ideally, such studies should also incorporate measurements of flight altitude so that birds flying above, or below, the collision risk window can be excluded from subsequent analyses. However, in collecting these data a key consideration needs to be whether the survey has sufficient power to detect change between the pre- and post-construction periods. The power to detect change is related to a variety of factors including the frequency of, and area covered by, the surveys as well as inherent spatial and temporal variability in seabird distribution and relative abundance (Maclean et al., 2013; Pérez Lapeña et al., 2010). This is a particular issue where the pre-construction population of a species is small, and is always likely to be an issue where baseline sampling has not taken account of statistical power for detection of change. This exacerbates the risks of a change in the number of birds using a site either giving the false impression of a significant effect (false positive response) or where no change is found, the results are wrongly interpreted as a lack of response to the presence of the wind farm by the particular species (false negative response). A recent review (Marine Management Organisation, 2014) of post-consent monitoring of offshore wind farms concludes that the power to detect such changes by existing studies is likely to be low and the responses of seabirds to wind farms may have been incorrectly quantified. Careful consideration must also be given to biases associated with survey methodology. In particular, data collected from different platforms (e.g. visual aerial surveys vs digital aerial surveys) can give very different estimates of abundance (Buckland et al., 2012). Consequently, when estimating macro-avoidance based on displacement as functional habitat loss, it is important to ensure that the data used to do so are directly comparable.

Ideally, the effect size and associated confidence intervals should always be reported as standard in the results of ecological studies (Masden et al., 2015; Nakagawa and Cuthill, 2007). However, of the studies we considered, only Vanermen *et al.* (2015) and Natural Power (2014) did so in respect to the studies of displacement and attraction. If these practices were adopted as standard when measuring avoidance behaviour, not only would it make it more straightforward to quantify avoidance rates and compare across studies, it would also give us an understanding of the uncertainty and variability surrounding these rates.

4.4. Future data collection — anticipatory or impulsive evasion

Radar can be deployed in order to investigate anticipatory or impulsive evasion of wind farms or turbines. However, deriving species-specific avoidance rates from data collected in this way can be challenging given the difficulty of identifying species from radar tracks. Where species-specific macro-avoidance rates have been derived using radar, this has been possible because the majority of tracks could be assigned to a single species (e.g. during mass migration events when only a few species are represented; Desholm and Kahlert, 2005; Petersen et al., 2006). However, recent studies have demonstrated effective use of radar monitoring in combination with visual observations in order to be able to identify more complex suites of species moving in and around wind farms (Skov et al., 2012). Ideally these studies should also aim to collect data on the vertical distribution of birds and in-flight changes in behaviour (e.g. flight speed and turning angles).

4.5. Future data collection — escape response

In order to collect data describing micro-avoidance, carefully designed experiments and analyses are required. Approaches such as the use of turbine mounted cameras (Desholm, 2005) may be suitable, but must be capable of detecting abrupt changes in flight direction and/or altitude. Given that micro-avoidance behaviour is likely to be an extremely rare event, careful consideration must be given to ensure that any methods used have the necessary statistical power to estimate robust avoidance rates.

5. Conclusions

Our study assesses the evidence for avoidance behaviour in five key seabird species, perceived to be at particular risk of collision, at three different spatial scales. We have demonstrated how the different types of data which have been collected fit within the framework for describing avoidance behaviour developed by May (2015). Whilst we have done this in the context of offshore wind farms, this approach is also likely to be applicable to other situations where collision risk is likely to be an issue, for example in relation to tidal turbines.

Lack of data on avoidance behaviour has been acknowledged as an issue for some time (Chamberlain et al., 2006). As the wind industry has developed both onshore and offshore, the evidence base has developed. This review summarises the evidence that has been collected to date and represents a significant step forward by presenting estimates of avoidance behaviour for five seabird species. It is important to acknowledge that these values are largely based on data from coastal, rather than offshore locations. However, in our opinion, this remains the best available evidence with which to quantify avoidance behaviour in seabirds. Significant knowledge gaps remain and key areas to be addressed include distinguishing between vertical and horizontal avoidance and gaining a better understanding of how seasonal and spatial processes may influence avoidance behaviour. This is particularly important given the rapid growth of the offshore wind sector and the potential for the cumulative impacts of collisions from multiple wind farms on species and populations of concern (Brabant et al., 2015; Busch and Garthe, 2017).

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Table 1 Summary of key studies of barrier effects, displacement and attraction for the five priority species (B = barrier effects; D = displacement; A = attraction and NR = no response). Black filled cells indicate species which were not covered by that particular study. Where given, estimated rates are either those reported in the study concerned or, derived from published effect sizes.

	Horns Rev (Petersen et al., 2006)	Horns Rev (Petersen et al., 2006)	Nysted (Petersen et al., 2006)	Egmond aan Zee (Krijgsveld et al., 2011)	Horns Rev 2 (Skov et al., 2012)	Egmond aan Zee (Leopold et al., 2013)	Princess Amalia (Leopold et al., 2013)	Alpha Ventus (Mendel et al., 2014)	Robin Rigg (Natural Power, 2014)	Greater Gabbard (APEM Ltd., 2014)	Blighbank (Vanermen et al., 2015)	Alpha Ventus (Welcker and Nehls, 2016)
Northern gannet	D	B (1.00)		B (0.64)	B (0.86)	D	D	NR	NR	D (0.95)	D (0.85)	D (0.92)
Lesser black-backed gull						D	NR	D			A (-4.25)	
Herring gull	A		NR			NR	NR		NR		A (-8.4)	A (-1.79)
Great black-backed gull						NR	NR		NR		NR	A (-2.00)
Black-legged kittiwake					B (0.69)	NR	D	D	NR		NR	NR
Gulls (*Larus spp.)*				B (0.18)	B (0.56)							

Table 2 Vertical meso-avoidance rates obtained for the five priority species and for birds classified as unidentified gulls from comparisons of the number of birds at rotor height pre- and post-construction, or the number of birds at rotor height inside and outside a wind farm. Values of 0 reflect no increase or decrease in the proportion of birds at rotor height, values >0 reflect a decrease in the proportion of birds at rotor height (avoidance) and values <0 reflect an increase in the proportion of birds at rotor height (attraction).

	Barrow (Barrow Offshore Wind Limited, n.d.)	**Egmond aan Zee** (Krijgsveld et al., 2011)	**Gunfleet Sands 2010/11** (GoBe Consultants Ltd., 2012; NIRAS Consulting, 2011)	**Gunfleet Sands 2011/12** (GoBe Consultants Ltd., 2012; NIRAS Consulting, 2011)	**Robin Rigg** (Natural Power, 2013)
Northern gannet	-0.59	0.49	[redacted]	[redacted]	[redacted]
Black-legged kittiwake	-0.41	0.20	-0.47	0.05	-1.00
Lesser black-backed gull	0.72	attraction	-0.44	0.00	[redacted]
Herring Gull	0.35	No change	-0.02	0.11	-8.00
Great black-backed gull	0.28	avoidance	-0.75	-0.53	-0.67
“small” gulls	[redacted]	-0.26	[redacted]	[redacted]	[redacted]
“large” gulls	[redacted]	no change	[redacted]	[redacted]	[redacted]
Gull *spp.*	-0.85	avoidance	-1.98	-1.13	[redacted]

Table 3 Data sources used to estimate micro-avoidance and within-wind farm avoidance rates for marine species. Rows in bold indicate sites from which data were used to derive within wind farm avoidance rates.

Wind Farm (citation)	**Survey Method**	**N Hours observations**	**N Turbines Covered**	**N Birds recorded during point counts**	**Reported Fatalities (N collisions directly observed)**	**Behavioural interactions with turbines**
Alpha Ventus (Schulz et al., 2014)	Remote Camera	8741	1	241	<1 (0)	Of 14 objects reliably identified as birds, at least 12 had successfully passed through the rotor swept area of the turbine. Whilst collisions were assumed, none were directly recorded by the cameras
Avonmouth (The Landmark Practice, 2013)	**Visual**	**108**	**3**	**5,616**	**1 (0)**	
Blyth (Rothery et al., 2009)	Visual	352	2	8,534	0 (0)	
Blyth Harbour (Newton and Little, 2009)	Visual	93	9	791	1,410-1,838[1] (0)	
Boudwijnkanaal (Everaert, 2014)	**Visual**	**34**	**5-7[2]**	**1,847**	**12 (0)**	
Bouin (Dulac, 2008)	**Visual**	**370**	**8**	**8,243**	**30 (0)**	
De Put (Everaert, 2014)	**Visual**	**18**	**2**	**54**	**2 (0)**	
Egmond aan Zee (Krijgsveld et al., 2011)[3]	Visual		6	1,610	0 (0)	Of 36 birds (2 lesser black-backed gulls, 4 great black-backed gulls, 2 starlings, 28 skylarks) recorded within 50m of a turbine, 33 were recorded as being beyond the reach of the turbine blades
Gneizdzewo (Zielinski et al.,	**Visual**	**620**	**19**	**4,443**	**1 (0)**	

2012, 2011, 2010, 2008)						
Greater Gabbard (RPS, 2011)	Visual	36	7	189	0 (0)	1 kittiwake noted making an evasive manoeuvre to avoid collision, no other birds reported close enough to turbines to require evasive manoeuvres
Groettocht (Krijgsveld et al., 2011)	Radar	39	7	6,825	5 (0)	
Haverigg (RPS, 2011)	Visual	42	8	836	0 (0)	
Hellrigg (Percival, n.d., n.d.)	**Visual**	**74.5**	**4**	**26,638**	**1 (0)**	
Kessingland (Wild Frontier Ecology, 2013)	**Visual**	**36**	**2**	**3,535**	**3 (0)**	**5 black headed gulls, 2 lesser black-backed gulls and 1 herring gull reported taking evasive action within 50m of turbines. No birds observed colliding**
Kleine Pathoweg (Everaert, 2014)	Visual	16	7	672	0 (0)	
Nysted (Desholm, 2005)	Remote Camera	476	1	55	0 (0)	Despite potential to record birds interacting with turbines, no birds were recorded within 20m of a turbine
Oosterbierum (Winkelman, 1992)[3]	**Radar**		**18**	**202,400**	**49 (0)**	
Walney I, Walney II, West of Duddon Sands, Ormonde & Barrow Offshore Wind Farms (Thaxter et al., 2017b)	GPS Tag	2112	270	2	0 (0)	2 lesser black-backed gulls spent 1.2% and 2.7% of their time within a 3-dimensional rotor swept area around turbines, neither collided with the blades
Waterkaaptocht (Krijgsveld et al., 2011)	Radar	39	8	14,430	6 (0)	
Yttre Stengrund (Pettersson, 2005)	Visual	219.5	5	404,146	4 (4)	
Zeebrugge (Everaert, 2014)	**Visual**	**43.7**	**4**	**2,491**	**7 (0)**	

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[1] Extrapolated from mean annual collision rates corrected for corpses lost at sea or undetected by observers. [2] Five turbines covered in 2001, seven turbines in 2005.[3] Total time not stated.

920 **Table 4** Within-wind farm avoidance rates for seabirds

Species	N birds observed (N collisions recorded)	Non-avoidance rate	Within-wind farm avoidance rate (± SD)
Lesser black-backed gull	101,746 (2)	0.0018	0.9982 (±0.0005)
Herring gull	546,047 (9)	0.0041	0.9959 (±0.0006)
Small gull spp.	1,598,953 (42)	0.0079	0.9921 (± 0.0015)
Large gull spp.	639,560 (14)	0.0044	0.9956 (± 0.0004)
Gull spp.	2,567,124 (139)	0.0107	0.9893 (± 0.0008)

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Highlights

- Seabird collisions with turbines are seen as a key concern for the offshore wind industry
- Understanding the extent to which seabirds avoid turbines is a key part of the impact assessment process
- We synthesise the knowledge of seabird interactions with offshore wind turbines
- We highlight that most avoidance behaviour is likely to take place away from the turbines
- We identify the key remaining gaps in knowledge and discuss the most appropriate approaches to fill these gaps