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Short Communication

Do birds respond to spiral markers on overhead wires of a high-voltage power line? Insights from a dedicated avian radar

Diego Pavón-Jordán [a], [*], Bård G. Stokke [a], Jens Åström [a], Kjetil Bevanger [a], Øyvind Hamre [a], Ellen Torsæter [b], Roel May [a]

[a] *Department of Terrestrial Ecology, Norwegian Institute for Nature Research (NINA), P.O. Box 5685 Torgarden, N-7485 Trondheim, Norway*
[b] *Department of Research and Development, Statnett, Nydalen Allé 33, 0484, Oslo, Norway*

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ABSTRACT

Growing human population demands the expansion of the energy transmission grid. Power lines represent a major death hazard for many species, especially birds. Addressing such a human-wildlife conflict requires detailed knowledge of how species use the aerial space and how they react to mitigation measures, such as flight markers. Here, we use a dedicated avian radar to study birds' flight behaviour at marked and unmarked sections of a power line in Norway. We investigate the effect of wire marking on the density of bird tracks, multidirectionality, perpendicularity and turning angle at increasing distance from a power line as well as the maximum turning angles and track height. In addition, the avian radar allowed us to compare flight behaviour between daytime and night-time. The density of bird tracks was lower during the daytime (when markers are visible) compared to night-time (markers are not visible). Furthermore, bird tracks (i) were more directional during daytime, especially at the marked section, (ii) were less perpendicular to the power line at the marked compared to the unmarked section, and (iii) performed more pronounced turning angles at the unmarked compared to the marked section. Moreover, tracks' maximum turning angle was largest at the unmarked section and the average track height was greater at the marked section of the power line. Our findings provide new correlative evidence of changes in birds' flight behaviour induced by flight markers on a power line's earth wire. Furthermore, we highlight the adequacy of dedicated avian radars to assess the efficiency of conservation interventions mitigating the impacts of overhead energy infrastructure (power lines, wind turbines) on the use of the aerial space by animals.

1. Introduction

Energy is a basic need for human wellbeing and its consumption is forecast to rise globally by 48% in the next three decades (Conti et al., 2016). Thus, securing energy supply to the increasing human population in the near future implies not

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* Corresponding author.
E-mail address: diego.pavon-jordan@nina.no (D. Pavón-Jordán).

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only increased energy production but also the expansion of the current energy transmission networks, which is anticipated to come at a high economic (Bernardino et al., 2018) and ecological cost (Biasotto and Kindel 2018; Pimm et al., 2014).

Power lines represent a direct hazard for many bird species (Martin, 2011) due to collision with overhead wires (Bernardino et al., 2018 and references therein) and electrocution (Hernández-Lambraño et al., 2018). Species that are reported to be especially susceptible (Martin, 2011) include several red-listed (Janss 2000; Martin and Shaw 2010; Morkill and Anderson 1991; Quinn et al., 2011) and game species (Bevanger 1995; Bevanger and Brøseth 2001). Power lines were estimated to kill nearly a billion individuals annually due to collision (Hunting 2002). This figure surely underestimates the current levels of mortality as the global electric grid has increased by 5% per annum since the early 2000s (Jenkins et al., 2010), when there were 65 million km of medium- and high-voltage power lines (so called 'transmission lines') around the world (Martin and Shaw 2010).

Because of the ecological and socio-economic relevance of this conflict between the (increasing) human need for energy supply and the conservation of bird populations (whether to meet biodiversity targets or as prey for hunters) has drawn considerable attention in the past decades (reviewed in e.g. Bernardino et al., 2018; Biasotto and Kindel 2018). However, the consequences of this human-induced mortality for population dynamics still remain unknown for most species (Barrientos et al., 2011; 2012; but see Bevanger et al., 2014; D'Amico et al., 2019).

A number of conservation interventions have been applied to try to reduce the fatalities of birds due to collisions with power lines (Bernardino et al. 2018, 2019; Sutherland et al., 2018). One such intervention is the marking of overhead (earth) wires with different type of flight markers (Bernardino et al., 2019), which has proved to be efficient in reducing bird collisions and mortality (reviewed in Barrientos et al., 2011; Bernardino et al., 2018). However, its efficiency in reducing bird collisions differs across studies (Barrientos et al., 2011; Bernardino et al., 2018; Jenkins et al., 2010; Martin and Shaw 2010), which prevented a recent meta-analysis to detect a strong effect of the marking on bird mortality (Bernardino et al., 2019).

Here, we use a dedicated avian radar to record birds' flight behaviour simultaneously at a marked and unmarked section of a high-voltage transmission power line crossing a wetland area in central Norway. Previous studies have assessed the efficiency of wire marking by comparing the number of carcasses found at marked and unmarked sections (Barrientos et al., 2011; Bernardino et al., 2018), rather than a direct investigation of how birds actually use the airspace close to the power lines and how they react to bird markers in flight (but see Brown and Drewien 1995; Deng and Frederick 2001). We hypothesized that spiral flight diverters (hereafter, markers) increase the conspicuousness of the earth wire leading to adjusted flight behaviour in response to the detection of the wire (i.e. increased rate of visual information gain; Martin, 2011) at the marked section relative to the neighbouring unmarked section. One of the main advantages of the avian radar is that it allows us to monitor birds' movements 24 h/day. Thus, we also compare flight behaviour during daytime (when the markers are visible to birds) and night-time (when the markers, which do not emit or reflect light, are less visible). Due to darkness, no effect of marking was expected at night while behavioural adjustment was expected during the daytime. Therefore, night-time and daytime are used as a *pseudo*-control and treatment, respectively. This is, to the best of our knowledge, the first study using a dedicated avian radar to assess the impact of such a conservation intervention on the birds' use of the aerial space around power lines.

2. Materials and methods

2.1. Study area

The study was carried out in a wetland area in Kleive (Møre og Romsdal county, Norway; Fig. 1) constituted by the Osvatnet lake and the Oselva river, which flows into the Osen Nature Reserve in the Fanne fjord. This region hosts a relatively high abundance of birds, such as wildfowl, common cranes (*Grus*), grey herons (*Ardea cinerea*), and white-tailed eagles (*Haliaeetus albicilla*)(Stenberg 2010). There was also migration of various species of thrushes (*Turdus* spp) during the study period (see below).

In Norway, there are currently ca. 180,000 km of overhead power lines throughout the country and the grid of transmission and regional distribution lines has increased with ca. 1000 km since the mid-2000s (Heien and Helen, 2018). For this study, we selected a high-voltage (420 kV) power line with three double-conductors and two earth wires (i.e. two vertical wire levels; Fig. S1) that perpendicularly crosses the Oselva river (Fig. 1). This power line represents an ideal study system because (i) it has adjacent sections with and without flight markers on the wires (section length of 480 and 460 m, respectively) to carry out a control − treatment study (see Bernardino et al., 2019). The flight markers installed on this power line are grey spirals (length = 37 cm; rod diameter = 12.7 mm; Fig. S2), which are placed on one of the two earth wires that cross the Oselva river (10 m distance between markers, Fig. S3). Also, (ii) there is a nearby place where the radar can function to its maximum performance (e.g. minimizing blind areas). Although the landscape around the power line was relatively homogeneous, there were habitat differences between the marked and unmarked sections of the power line, which we accounted for (Fig. 1, Supplementary Table S1).

2.2. Avian radar bird surveys

The ROBIN 3D Flex Radar System (Robin Radar Systems, the Netherlands) has been specifically developed for monitoring bird movements in the three dimensions of aerial space. It consists of two modules; an X-band Frequency Modulated

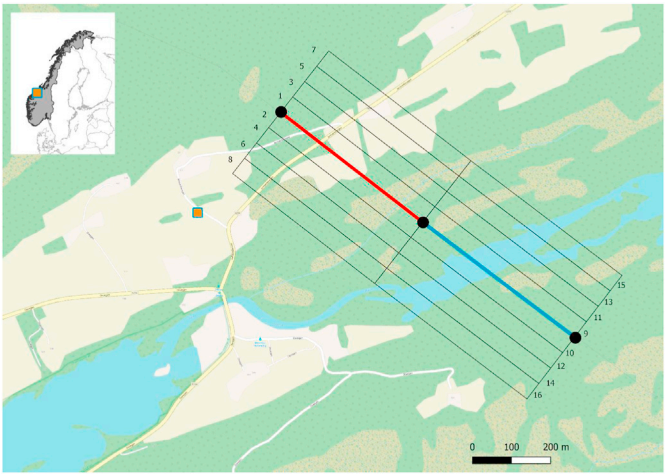

Fig. 1. Location of the dedicated avian radar (Lat 62.79578, Lon 7.72239) at the study site in Osen, Kleive (Molde municipality), Møre og Romsdal county, Norway. The map shows the marked (blue line) and unmarked (red line) sections of the power line, the masts (filled black dots), the avian radar (filled orange square) and land use categories intersecting with the power line (blue: waterbody; green: forested area; yellow: agricultural land; brownish: mires; see Figs. S1-S3.). The 50 m block design (black empty polygons) with the numbering used in the block analysis are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Continuous Wave (FMCW) vertical radar and an S-band horizontal radar (FAR2167DS; Furuno) designed for automatic detection and tracking of birds. The FMCW radar is mounted on a stand (2.5 m height AGL) and rotates both horizontally and vertically to record the flying height of tracked birds in user-defined directions (max. range of 3.5 km). The S-band radar rotates in the horizontal plane for 360° coverage (max. range of 10 km).

Bird movements at the power line were recorded continuously (24 h/day) using this dedicated avian radar for two months during autumn migration in 2016 (1 September – 31 October). The radar tracks do not give information on the species, but tracked individuals are classified into flocks, small-, medium-, and large-sized birds. The closest distance from the radar to the power line (unmarked section) was 280 m (Fig. 1). The distance from the radar to the beginning and end of the marked section was 600 and 1000 m, respectively (Fig. 1). A total of 356,335 tracks were recorded and stored in a PostgreSQL database. Tracks made by vehicles and airplanes are also identified by the software and were removed from the data prior to analyses.

2.3. Data preparation

We first selected from the database all tracks (or the segments of the tracks that cross the power line) that were heading towards the power line ($n = 210{,}323$) to properly assess bird behaviour when approaching the power line. We then created 50 m bins (hereafter, blocks) within 200 m from the power line (i.e. 4 blocks at each side of both sections of the power line, $n = 16$; see Fig. 1). We used these blocks to aggregate bird tracks into four ‘distance’ groups (50 m, 100 m, 150 m, and 200 m from the power line). Our four response variables (see *Data analysis*, below) were derived from this aggregation. At the same time, the 16 blocks would capture the spatial dependency of tracks within blocks (spatial correlation), potential habitat differences across blocks, and the potential decrease in the detection capability of the radar recording birds with distance (May et al., 2017). Lastly, although the radar did not record height data for all the tracks due to a technical problem, we queried a separate dataset only containing tracks with height data at the intersecting point with the power line ($n = 713$).

2.4. Data analysis

Our modelling exercise consisted in a control-impact design (see Bernardino et al., 2019), including a spatial gradient approach. The effects of wire marking (hereafter *Marker*) on the number, directionality, perpendicularity, and turning angle of bird tracks (see description of each response variable below) were evaluated in interaction with distance from the power line (hereafter *Distance*) and time-of-the-day (hereafter *Time*). All tracks were binned in each of the 50 m blocks (see above; Fig. 1). Hence, *Distance* takes the values of 50, 100, 150, and 200, which we treated as a continuous covariate. The variable *Time* (categorical variable with two levels) accounted for another (temporal) control-impact assessment, where we compared night-time (control; low conspicuousness of the markers) with daytime (treatment; high conspicuousness of the markers). Daytime was defined based on the average time period between sunrise and sunset for September and October (07:00–20:00 and 08:00–18:00, respectively).

Within each unique spatio-temporal cluster (*Time* × *Distance*), we counted the number of tracks recorded by the avian radar at both the marked and the unmarked sections of the power line. Although all the 16 blocks were within the radar range, we found some cluttered areas. Cluttered areas are regions within a radar range where the radar is blind due to undesired echoes from different objects in the landscape. In our case, these came mainly from ground clutter. Thus, we calculated the **density of tracks** $\left(\frac{\mathit{Number\ of\ tracks}}{\mathit{Area\ surveyed\ by\ radar}}\right)$ instead of the raw number of tracks (Supplementary Table S1). We defined **multidirectionality** within each spatio-temporal cluster as the standard deviation of the cosine of the track directions (bearing). Multidirectionality values were cosine-transformed prior to analysis to meet the normality assumption (e.g. Zuur et al., 2007). Thus, low values of multidirectionality signify more (uni)directional (i.e. straighter) trajectories. We defined **perpendicularity** as the proportion of tracks within each spatio-temporal cluster that went perpendicular to the power line relative to those that went parallel (±45°) to the power line. **Turning angle** within each cluster was defined as the average turning angle for all tracks, calculated as $\frac{(1-\cos(\Delta\ azimuth))}{2}$. This resulted in trajectories ranging from 0 (no change in trajectory, i.e. 0°) to 1 (full turn, i.e. ± 180°). We also calculated the maximum angle of each of the tracks for an additional analysis of birds' behaviour approaching a power line. Note that all tracks included in these analyses were heading to the power line.

For each of the four dependent variables (i.e. density of tracks, multidirectionality, perpendicularity, and turning angle), we ran all possible combinations between the three main effects (*Marker*, *Distance,* and *Time*), as well as all two- and three-way interactions ($n = 19$) within an Information Theoretic approach and ranked them based on their Akaike's Information Criterion (AIC) (Burnham and Anderson 2002). Models including uninformative parameters (i.e. when a model is ranked within 2 AIC units from the top-supported model but only differed by including one more covariate with low explanatory power) were dismissed to properly calculate the AIC weights of the different covariates (Arnold 2010). After this, if competing models (within 2 AIC units) were still found, we model averaged the estimates (Arnold 2010; Burnham and Anderson 2002). 'Density of tracks', 'directionality' and 'turning angle' were modelled assuming a Gaussian error distribution, and 'perpendicularity' was modelled assuming a Binomial distribution (number of perpendicular over parallel tracks). To account for the dependency between observations from the same day, we included *Julian day* as a random effect in all models. We also included *Block* as a random effect to account for the dependency of observations within the same mean distance to the radar as well as potential differences in the habitat composition in each block that may trigger different flight behaviour. Lastly, we used the 'emmeans' package (Lenth 2019) to perform *post-hoc* contrasts in order to identify differences in slope estimates between the factor levels. We additionally investigated differences in the maximum turning angle of the tracks at the marked and unmarked sections of the power line by fitting a linear model to the track-specific maximum turning angles. Lastly, we fitted a linear model (Gaussian error distribution) to the subset of data with eight information (height as a continuous response variable) to assess differences between the height at which birds crossed both sections of the power line. All (generalized) linear mixed-effects regression models were built using the 'glmmTMB' package (Magnusson et al., 2017) in R 3.6. (R Core Team, 2020).

3. Results

3.1. Density of bird tracks

The full model including the three-way interaction had the lowest AIC (Table 1; conditional $R^2 = 0.48$. The number of tracks was lower during daytime compared to night-time, but only at the marked section (Fig. 2). In addition, the number of tracks declined with distance in the marked section but not in the unmarked section (Fig. 2b).

3.2. Multidirectionality of bird tracks

The best model according to AIC included *Marker*, *Time* and the interaction *Marker* × *Time* and *Distance* × *Time* (Table 1; conditional $R^2 = 0.57$) A competing, simpler model including *Marker*, *Time* and the interaction *Marker* × *Time* appeared to have similar explanatory power (Table 1; $R^2 = 0.57$). The interaction *Distance* × *Time* had, thus, little explanatory power, as shown also by the AIC weights after model-averaging across these two models (Table 2). Bird tracks were more directional (i.e. lower multidirectionality) at the marked section of the power line, especially during daytime (post-hoc contrast *daytime vs night-time* at the marked section; Estimate (SE) = −0.01 (0.001), df = 2223, T = −6.71, $p < 0.001$; see also Fig. 3a, Supplementary Fig. S4).

Table 1
Models ranked according to the AICc. Only models with ΔAIC <2 from the top-ranked model are shown.

Model	df	AICc	ΔAICc	weight
NUMBER OF TRACKS				
Distance + Time + Marker + Distance × Marker + Distance × Time + Time × Marker + Distance × Marker × Time	11	10,973.4	0	1
MULTIDIRECTIONALITY				
Time + Marker + Distance + Time × Marker + Distance × Time	9	−9714.6	0	0.51
Time + Marker + Distance + Time × Marker	8	−9714.71	0.11	0.49
PERPENDICULARITY				
Distance + Time + Marker + Marker × Time	9	6906.63	0	1
TURNING ANGLE				
Distance + Time + Marker + Marker × Time	7	−5628.99	0	1

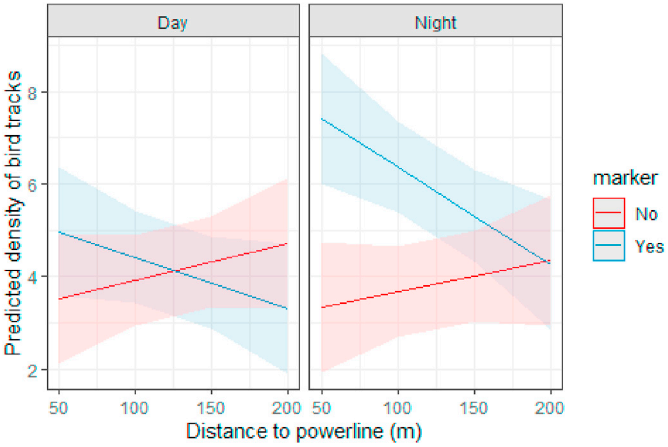

Fig. 2. Predicted density of tracks at the marked and unmarked sections of a high-voltage power line at Kleive, central Norway. Results shown are depicted from the model with lowest AIC (full model, see also Table 1). The shaded area represents the 95% confidence interval.

3.3. *Perpendicularity of bird tracks*

The model with lowest AIC included the three main terms and the interaction *Marker* × *Time* (Table 1). Our results showed that *Perpendicularity* was lower at the marked section compared to the unmarked section (Fig. 3b).

3.4. *Turning angle of bird trajectories and maximum turn*

The best model included the additive effect of the main terms *Marker*, *Time*, *Distance*, and the interaction *Marker* × *Time* (Table 1). Turning angles were larger at the unmarked section compared to the marked section and at daytime compared to night-time (Fig. 3c). In addition, the maximum turning angle of the tracks was, on average, largest at the unmarked section compared to the marked section ($Z = -50.7$, $P < 0.001$; Fig. 4a).

3.5. *Height at crossing the power line*

Results of the linear model comparing the subset of the data with information on height at crossing between the marked and unmarked sections showed that birds crossed the power line, on average, 8 m higher at the marked section than at the unmarked section ($Z = 3.94$, $P < 0.001$; Fig. 4b).

4. Discussion

Efficient conservation measures can only be achieved if there is a good understanding of wildlife responses to both anthropogenic habitat transformation and the mitigation interventions implemented to alleviate such impacts (Sutherland et al., 2004). After accounting for potential confounding effects that landscape heterogeneity at the power line and detectability of tracks linked to the distance from the radar may have on bird flight behaviour, our findings underline the potential of spiral flight markers to reduce the risk of bird collisions with power lines in our study area, especially during daylight when the flight markers are more visible to birds. In addition, we highlight the adequacy of dedicated avian radars for continuous monitoring of the potential impacts of human-made infrastructures on birds' flight behaviour (see also Nilsson et al., 2018).

Table 2
Sum of weight of each covariate across all models with delta AIC <2 (after model averaging if more than one competing model was found). Covariates not selected in the top models (i.e. uninformative parameters) are indicated with (–).

Covariate	Sum of weights			
	Number of tracks	Multidirectionality	Perpendicularity	Turning angle
Distance	1	1	1	1
Marker	1	1	1	1
Time	1	1	1	1
Marker × Distance	1	(–)	(–)	(–)
Distance × Time	(–)	0.51	(–)	(–)
Marker × Time	1	1	1	1
Distance × Time × Marker	(–)	(–)	(–)	(–)

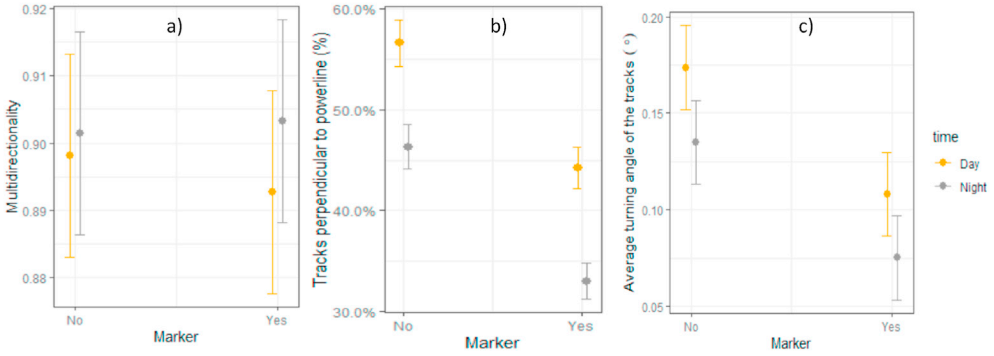

Fig. 3. Model results. a) Multidirectionality in bird tracks at a marked and unmarked section of the power line at Kleive, central Norway. Low values of multidirectionality represent more straight tracks. Results shown are depicted from the model-averaged estimates of the two competing models with lowest AIC (see also Table 1). b) Perpendicularity in bird tracks at the marked and unmarked sections by time of the day. Results shown are depicted from the model with lowest AIC, which included the main terms and the interaction Marker × Time (Table 1). c) Average turning angle of bird tracks depicted from the model with lowest AIC, which included the three main effects and the interaction Marker × Time (Table 1). The vertical bars in all three panels show the standard error.

4.1. *Density of bird tracks*

The reduced density of tracks at the marked section of the power line during daytime, compared to the night-time, suggests that birds may detect the flight markers and thus avoid flying around this section. Moreover, this (anticipatory) evasion behaviour (May, 2015) when the markers are visible is also supported by the fact that we found no differences in the density of bird tracks between daytime and night-time at the unmarked section.

The declining density of flying birds with distance to the marked section might seem counterintuitive as one would expect to find fewer birds flying close to the power line than farther away, also due to corona light (Tyler et al., 2014). However, our finding did show that the decline in number of tracks with distance was less steep during daytime compared to night-time. This suggests that the number of tracks during both day- and night-time was similar at large distances (200 m from the power line), but with lower density of birds closer (50 m) to the power line during daytime. In other words, when the markers are visible to birds (i.e. daytime), fewer birds were recorded flying close to the power line. This temporal difference was not significant farther (200 m) from the marked section of the power line.

The lower density of flying birds recorded by the avian radar at the marked section of the power line during daytime compared to night-time may well be associated with a behavioural response to the presence of the markers. If the markers would not provoke any behaviour response from birds and this spatial pattern would be linked to other factors (e.g. habitat; e.g. D'Amico et al., 2018), the decline in the density of tracks recorded by the radar with distance to the power line at daytime and night-time should be similar. Since markers are not visible during night-time, more birds fly close (<50 m) to the power line compared to during daytime. Birds will be able to detect the markers during daytime and thus move to other places,

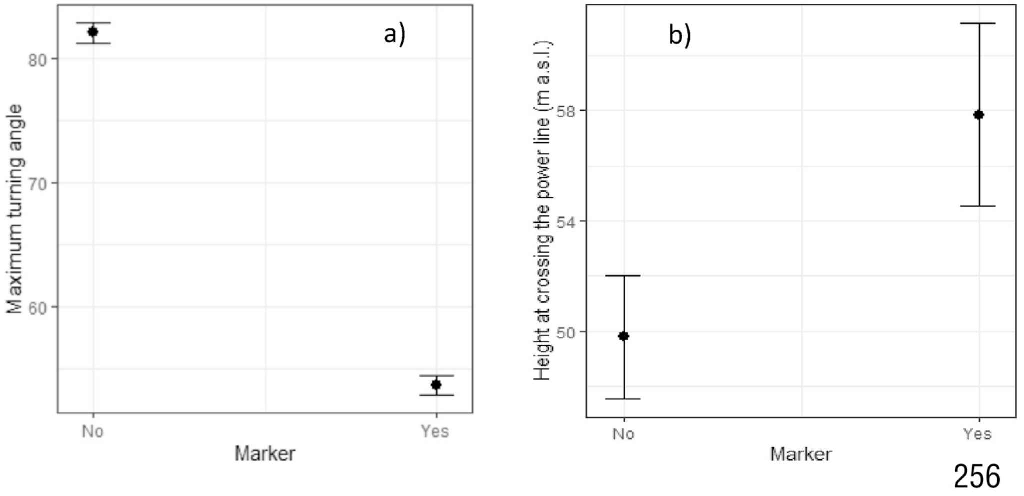

Fig. 4. a) Predicted maximum turning angle (and the standard error) of bird tracks and b) height (meters above sea level) at which tracks crossed both sections of the high-voltage power line at Kleive, central Norway. The vertical bars show the standard error.

which may be out of the monitored area (i.e. blocks). Observational studies have reported similar effects of flight markers on birds' behaviour in other wetland areas in Colombia (De La Zerda and Rosselli 2000) and the United States (Brown and Drewien 1995). Thus, by preventing birds to fly close to the power line, these spiral markers potentially contribute to the reduction of bird mortality risk by collisions with power lines (Alonso et al., 1994; Barrientos et al., 2012; Morkill and Anderson 1991; Yee and Marcus, 2008).

4.2. Bird behaviour

Flight height is thought to be the main behavioural reaction to the presence of a power line (Barrientos et al., 2011). Although the avian radar used in this pilot study recorded little information on flight height due to technical problems, we could show important differences in the flight height of birds at the two sections of the power line. Birds flew on average at an altitude of ca. 50 m and 58 m a.s.l. at the unmarked and marked sections of the power line, respectively. Given that the unmarked and marked section are situated at 23 and 24 m a.s.l. and that the earth wire, where the markers are installed is ca. 25 m above the ground, birds barely crossed over the power line at the unmarked section but did so at safer distance at the marked section.

In addition, our findings provide, for the first time, accurate insights into other flight behavioural reactions that can be associated with the presence of the markers on the overhead wires. Firstly, bird trajectories were more directional (straighter) during daytime compared to night-time, especially at the marked section of the power line. A possible explanation is that birds see the power line when there is daylight, especially when the markers are present, which may trigger a similar evasive reaction (see Bhagavatula et al., 2011). Furthermore, visual fields of nocturnal species appear to be more diverse than diurnal species (Martin 2007), which may also contribute to the higher track multidirectionality at night (see also Martin, 2011). Although we accounted for differences between the marked and unmarked sections of the power line (block analysis), the presence of the river that flows under the marked section may strongly influence birds' behaviour, especially that of waterbirds. Waterfowl and herons were seeing flying from the fjord to the lake (and vice versa) following the river, crossing safely the marked section of the power line at considerable height (B. G. Stokke, pers. comm.). Moreover, irrespective of marking, diurnal migration might be more common than nocturnal migration in this area, thus, contributing to the more directional flight during daytime compared to night-time.

Secondly, birds flying towards the power line tended to fly more perpendicular to the power line more often at the unmarked than the marked section of the power line, which could be related to a response to the presence of the markers. Although the markers are conspicuous during daytime, we found that the proportion of tracks perpendicular to the power line was larger at daytime compared to night-time. Similarly to the case of multidirectionality above, this temporal pattern might be associated to a stronger migration during daytime than at night-time. The lack of sufficient height data prevented us to explore the interaction of time of the day and marker with altitude of the track to properly assess the actual threat of the power line to those birds, as these birds might be flying perpendicular to the power line but at a safe distance from the wire (Barrientos et al., 2011; Luzenski et al., 2016; Morkill and Anderson 1991).

Thirdly, birds flying at the unmarked section of the power line performed on average more pronounced turns in flight compared to those at the marked section. This result suggest that the unmarked wire might suddenly appear as an obstacle in the aerial space. This is also supported by our separate analysis of comparing the maximum turning angle of all tracks heading to both sections of the power line, which showed a much larger maximum turning angle at the unmarked compared to the marked section of the power line. Since reducing speed to avoid collision is aerodynamically impossible for most species (Martin, 2011), birds in this situation respond strongly by performing abrupt turns to adjust flight direction and height. On the other hand, the higher conspicuousness of the marked wires may allow bids to adjust flight direction and height gradually. Changing flight direction to avoid marked wires has been reported for some species (Alonso et al., 1994; Morkill and Anderson 1991). However, in a meta-analysis, Barrientos et al. (2011) found no difference in birds approaching adjacent marked and unmarked sections of a power line. Turning angles were also smaller during night-time compared to daytime, which is in line with a previous observational study reporting that nocturnal birds were less responsive to the presence of a power line in a wetland area in the US (Deng and Frederick 2001).

Our results suggest that, overall, markers may trigger flight behavioural responses (e.g. turning and changing direction) that facilitate bids to avoid approaching the power line or to increase the flight height to cross over it safely. Most bird species are not able to see 'what lies ahead' in high resolution when in motion in the open airspace (Martin, 2011). Thus, our findings have important conservation implications because, for the first time, we provide evidence of a reduced number of birds and changes in flight behaviour that could be associated with the presence and visibility of spiral flight markers. Although our study has some limitations (i.e. did not provide sufficient amount of flight height data), we believe that the findings presented here represent new evidence of true behavioural responses of birds to the spiral markers installed on the earth wire of this power line. Future radar studies must have a previous analyses of the terrain to minimise the cluttered areas in the region of interest (i.e. around the power line), should place the radar in an optimal location to avoid potential differences in detectability between marked and unmarked sections (if they are at different distance from the radar), and must ensure the recording of height data to fully understand birds flight behaviour at power lines (e.g. whether birds crossing the power line do so flying well above the wires and if the markers trigger such a response in comparison to the unmarked wires). The effectiveness of flight markers might however vary depending on the spacing, size and type of marker as well as the habitat surrounding the power lines, bird species and season (Barrientos et al., 2011; Bernardino et al., 2019; Martin and Shaw 2010;

Quinn et al., 2011), and thus generalisations of our findings must be made with caution. Moreover, monitoring bird flight behaviour at power lines with different flight markers and configuration in different habitats is critical to fully understand how bird respond to this particular conservation intervention. Avian radars have traditionally been used to study migration (Nilsson et al., 2018) but, in an era where monitoring data must play a critical role in driving efficient evidence-based conservation (Sutherland et al., 2004), the prospects for using such a tool to assess the impact of the development of energy infrastructure (e.g. wind turbines and power lines) on species using the areal space (e.g. birds and mammals in flight) are very promising.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01363.

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