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Species-Specific Effects of a Sound Prototype to Reduce Bird Use of Powerline Poles

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Abstract: Powerlines pose a significant threat to many bird species, impacting their conservation. Current research focuses on developing methods to mitigate bird mortality due to electrocution and collisions with powerlines. In this study, we designed a sound prototype to be installed on infrastructure poles, including powerlines, aiming to reduce their use by birds. We conducted bird surveys over 47 days, from February to May 2020, in five light poles: the central pole where the device was installed (0 m), two poles at 25 m, and two poles at 50 m from the central pole. The first 10 days served as a control period with the deterrent device switched off, followed by 37 days with the device switched on. In total, we recorded 1945 bird observations, of which 1569 occurred with the device on. The device was triggered by bird movements, resulting in 588 reactions to sound. When activated, 10.6% of large- and medium-sized birds were flushed from the surveyed poles: 2.6% were already perched and flushed due to the sound, 3.9% were prevented from perching, and 4.1% were flushed after perching, thereby reducing the risk of electrocution. Among the birds perching or approaching the pole where the device was installed, 25% were deterred by the sound. The black kite, *Milvus migrans*, was the most reactive species to the device (54.3% flushed at 0 m, and 8.8% flushed at 25 and 50 m), while the white stork, *Ciconia ciconia*, showed the least sensitivity to the disturbances (14.4% flushed at 0 m, and 2.7% flushed at 25 and 50 m). The corvids exhibited a response rate between the other two species (33.3% flushed at 0 m, and 6.8% flushed at 25 and 50 m). We identified significant limitations to this prototype and proposed recommendations to improve its efficiency.

Keywords: bird electrocution risk; deterrent prototype; medium- to large-sized birds; powerlines; southern Portugal

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1. Introduction

Electrocution and collision with powerlines are significant causes of mortality for many bird species, posing a severe threat to their populations [1–3]. Electrocution, particularly in medium- to high-voltage distribution powerlines, is among the main conservation problems for some bird species [4–7]. Large- and medium-sized birds, such as storks, diurnal and nocturnal birds of prey, and corvids, are especially susceptible to electrocution due to their frequent use of powerlines and their poles [1,8,9] for perching, roosting, and nesting, and as strategic hunting spots [2,10]. Electrocution typically occurs during landing or take-off from a pole, while collisions happen in flight when birds are unaware of the powerlines as obstacles [11].

To mitigate the negative impacts of powerlines on birds, including several endangered species, some potential solutions have been proposed and implemented in the last decades [8,12–14]. These interventions include modifications in pole design and characteristics, such as the use of safe and non-conductive materials (e.g., wood or fiberglass); the installation of devices designed to prevent perching and nesting; and making structural changes to the voltage levels of older powerlines within the same corridor and often using the same poles [13,15–19]. Despite these efforts, bird mortality due to electrocution remains a persistent problem, and the scale and demographic consequences are still not well understood [20–24]. Developing effective methods to reduce electrocution continues to be a relevant area of research, even after more than four decades of study and practical applications. In response to this ongoing challenge, we designed and tested a sound prototype aimed at minimizing the use of electric poles by medium- and large-sized birds, thereby reducing the risk of electrocution.

2. Materials and Methods

2.1. Study Area

We conducted this study in the inter-municipal landfill of Évora (38°50′15.75″ N, 8°02′61.59″ O), located in southern Portugal and managed by GESAMB (Environmental and Waste Management Company). These facilities provide exceptional conditions to assess the efficiency of the deterrent prototype due to the high concentrations of medium- to large-sized birds and the abundance of light poles regularly used by birds where the prototype can be installed (Figure S1). The surrounding area of the landfill comprises open woodlands of cork oaks, *Quercus suber*, and holm oaks, *Q. rotundifolia*, with management practices including cattle and sheep grazing. The region features a typical Mediterranean climate with average temperatures ranging from 10.4 °C in winter to 22 °C in summer and an average annual rainfall of 799.1–1091.8 mm, falling mainly from October to March [25].

2.2. Prototype Description

The deterrent prototype includes a motion detection system based on infrared sensors and a sound device. It measures an area approximately 40 cm wide × 50 cm high and weighs about 2 kg. This device reproduces sounds in mp3 format, with an intensity between 20 Hz and 20 kHz up to 100 dB, and it is equipped with five passive infrared sensors (PIR) to detect surrounding movements up to 12 m (Figure 1). Upon detecting motion, the device plays pre-selected audible sounds with frequencies and time intervals (5–7 s) that change randomly to prevent bird habituation to a specific frequency pattern. The selection of sounds, stored on a Micro SD Card, includes attention-grabbing elements such as a siren, barking dogs, gunshots, and church bells, each reaching a peak of 100 dB. This device is powered by a 12 V 45 Ah battery attached to the bottom of the pole.

2.3. Field Testing of the Device

We installed the deterrent device on a light pole at the landfill's periphery and monitored it between February and May 2020 (Figure S2). To minimize installation-related disturbances, we allowed a three-day accommodation period before starting data collection. The initial 10 days of monitoring served as the experimental control, and the device was kept switched off. After this period, the device was switched on and we surveyed the poles for 10 additional consecutive days. The following monitoring involved keeping the device switched on four days a week for six weeks, with the exception of the seventh week which only comprised three days due to logistic constraints. Monitoring consisted of surveys, each lasting four hours and starting at 14 h 30. One observer, positioned at ca. 70 m from the device and concealed inside a car, recorded all medium- and large-sized birds (the size of a carrion crow, *Corvus corone*, and above) perching or approaching the light poles. The full record also included the species identification, the distance of the focal poles to the device (see below), the duration of the bird's stay on the pole (if perched), and every time the device was activated (i.e., produced sound). We also recorded the reactions of the individuals towards the prototype sound: (1) flushed (before or after perching) vs. did not flush (perching or remaining perched on the poles), and (2) perched vs. did not perch (was flushed before perching). We considered a flushing event to be whenever the individuals became restless and flushed during the playing period while perching, or when they were prevented from perching. We monitored five light poles: a central pole where the device was installed (0 m), two poles distancing 25 m, and two poles distancing 50 m from the central pole in each direction. This approach aimed to evaluate any potential reduction in noise level with increasing distance. However, due to the low range of the movement sensor, recording the effect of the device's sound on the poles at 25 and 50 m away was only possible when another bird activated the device. The records did not specify which sound was playing during the flushing events.

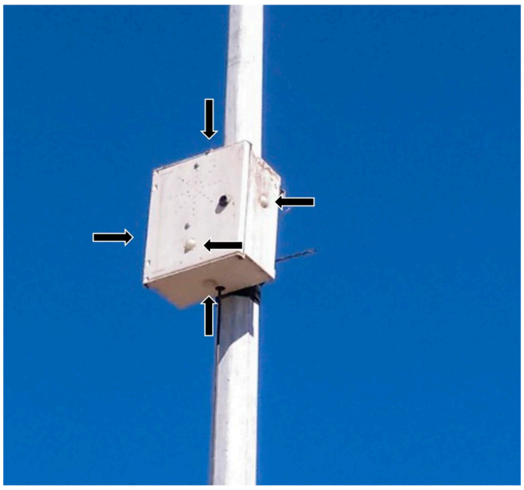

Figure 1. Deterrent device with the location of the PIR sensors (indicated by arrows).

Given the common occurrence of the carrion crow and common raven *Corvus corax* species in the study area, we grouped these two relatively similar species as *Corvus* sp. (corvids) in the analysis to minimize potential incorrect identifications.

2.4. Data Analysis

We evaluated the effectiveness of the deterrent device on bird behavior. We used a chi-square test to achieve the following: (1) To compare the number of birds perching or approaching the poles by species between the periods with the deterrent device switched off and on. In addition, we applied chi-squared tests to (2) compare the number of birds that flushed vs. the number of birds that did not flush while perching or approaching the central pole (0 m) and the farthest poles (25 and 50 m) with the deterrent device active, and (3) to compare the number of birds approaching the device that landed and stayed, perched and flushed afterwards, and those that did not perch the poles with the deterrent device active. Moreover, we performed a Generalized Additive Model (GAM) to model the accommodation effect of birds to the device over the periods. We used the "mgcv" package (version 1.9-1) [26] and included "Period" as a smooth term, and flush vs. did not flush as a categorical predictor. Significance was set at 0.05 for all tests. All analyses were conducted using R 3.6.3 [27] and RStudio 1.2.5042 [28].

3. Results

During the study period, we recorded 1945 individual bird observations either perching or approaching the five monitored poles: 844 (43%) white storks, 759 (39%) corvids (carrion crows and common ravens), and 342 (18%) black kites. In the initial 10 days when the device was switched off, we observed 376 individuals: 66% were corvids, 21% were white storks, and 13% were black kites (Figure 2A). During the following 37 days of monitoring, distributed across 8 periods with the device switched on, we recorded 1569 individuals: 49% white storks, 32% corvids, and 19% black kites (Figure 2A, Table S1). The number of white storks increased significantly with the device turned on ($F(8) = 4.52$, $p = 0.017$), while the number of corvids significantly declined ($F(8) = 8.73$, $p = 0.003$). However, the number of black kites did not show a significant difference between the device being off and on ($F(8) = 2.49$, $p = 0.066$) (Figures 2A and 3A–C, Table S1).

While the device was switched on, 262 birds approached the central pole (0 m), coming within the necessary distance to trigger the motion detector. However, only 164 (62.6%) of them actually activated the detector and triggered the sound. We recorded the reactions of 588 individuals, at all distances, towards the prototype sound, of which 337 (57%) were white storks, 136 (23%) were corvids, and 115 (20%) were black kites. These events included 89.5% of birds that did not flush and 10.5% that flushed in response to the sound.

Among the individuals that flushed in response to the device's sound, most occurred at the central pole (66.2%), whereas 27.4% flushed from the poles at 25 m, and only 6.5% from the poles at 50 m (Figure 2B, Table S2). At the central pole, we found a significant difference in the birds that flushed vs. those that did not among species ($\chi^2(2) = 23.31$, $p < 0.001$), suggesting the likelihood of flushing events are associated with species. White storks had the fewest flushing events (14.4% flushed vs. 85.6% did not flush), followed by the corvids (33.3% flushed vs. 66.7% did not flush). Black kites were the most reactive species to the sound (54.3% flushed and 45.7% did not flush) (Figures 2C and 4A–C, Table S2). Of the birds approaching the central pole, 25% were deterred by the sound. At the farthest poles (25 and 50 m), we observed similar patterns with significant differences among species as well ($\chi^2(2) = 5.822$, $p = 0.047$) (Figures 2D and 4A–C, Table S2). Among the birds approaching these poles, 5% were deterred by the sound.

The deterrent device prevented bird perching in 3.9% of the events, while in 6.7% of the events, birds were flushed after perching; 4.1% perched while the device was active and flushed afterwards, and 2.6% were already perched when the device was activated and then flushed.

In 55.9% of the events, the birds approaching the poles landed and stayed while the device was active, and in 33.5% of the events, birds that were already perched did not flush. These events were distributed with 43.5% occurring at 25 m, 33.1% at 50 m, and 23.4% at 0 m (Figure 2B, Table S2).

The perching behavior varied significantly among the three species ($\chi^2(4) = 17$, $p = 0.002$). White storks had the highest proportion of individuals that landed and stayed perched, with relatively few instances of not perching, or perching and flushing afterwards. Corvids predominantly perched and flushed afterwards; however, they rarely did not perch while the device was active. In contrast, black kites were the most sensitive species, showing the highest proportion of events where they either avoided perching or perched and flushed afterwards, and the lowest proportion of individuals that landed and stayed perched (Figure 2E).

The number of birds flushing from the device did not show significant differences across time periods, indicating no accommodation effect (GAM model; $F = 0.244$, $p = 0.63$). The model explains approximately 40.4% of the variance, suggesting a moderate fit to the data (adjusted $R^2 = 0.312$).

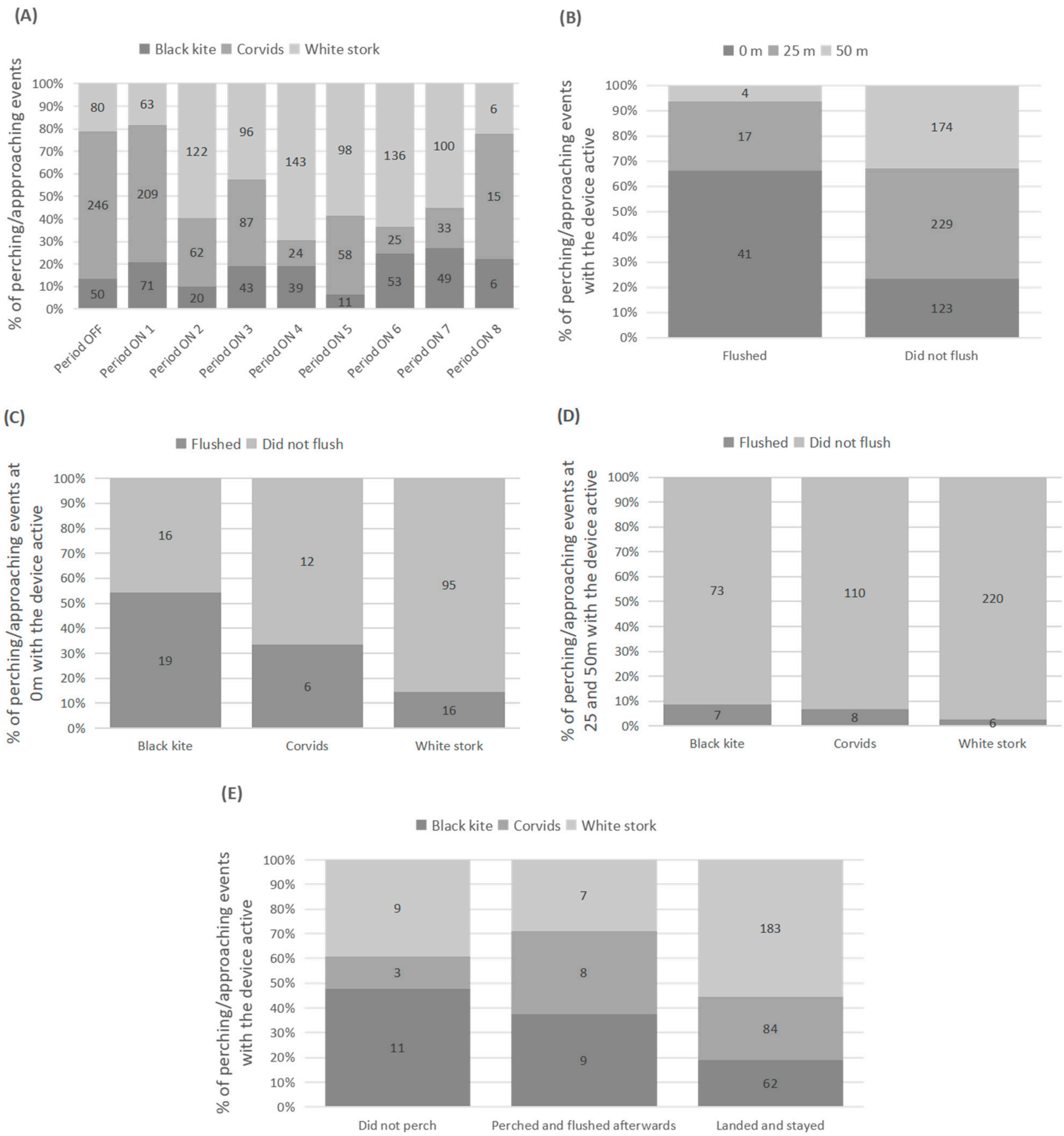

Figure 2. (**A**) Proportion (%) of white storks, corvids, and black kites perching and approaching the poles with the deterrent device (prototype) switched off and with the device switched on (8 periods). (**B**) Proportion (%) of individuals (all species pooled) that flushed and did not flush in response to the sound of the device according to the distance of the light pole to the deterrent device (0, 25, 50 m). (**C**) Proportion (%) of white storks, corvids, and black kites that flushed and did not flush on the central pole (0 m) in response to the sound of the device. (**D**) Proportion (%) of white storks, corvids, and black kites that flushed and did not flush on the farthest poles (25 and 50 m) in response to the sound of the device. (**E**) Proportion (%) of white storks, corvids, and black kites that did not perch, perched and flushed afterwards, and landed and stayed perched at the poles while the sound was active.

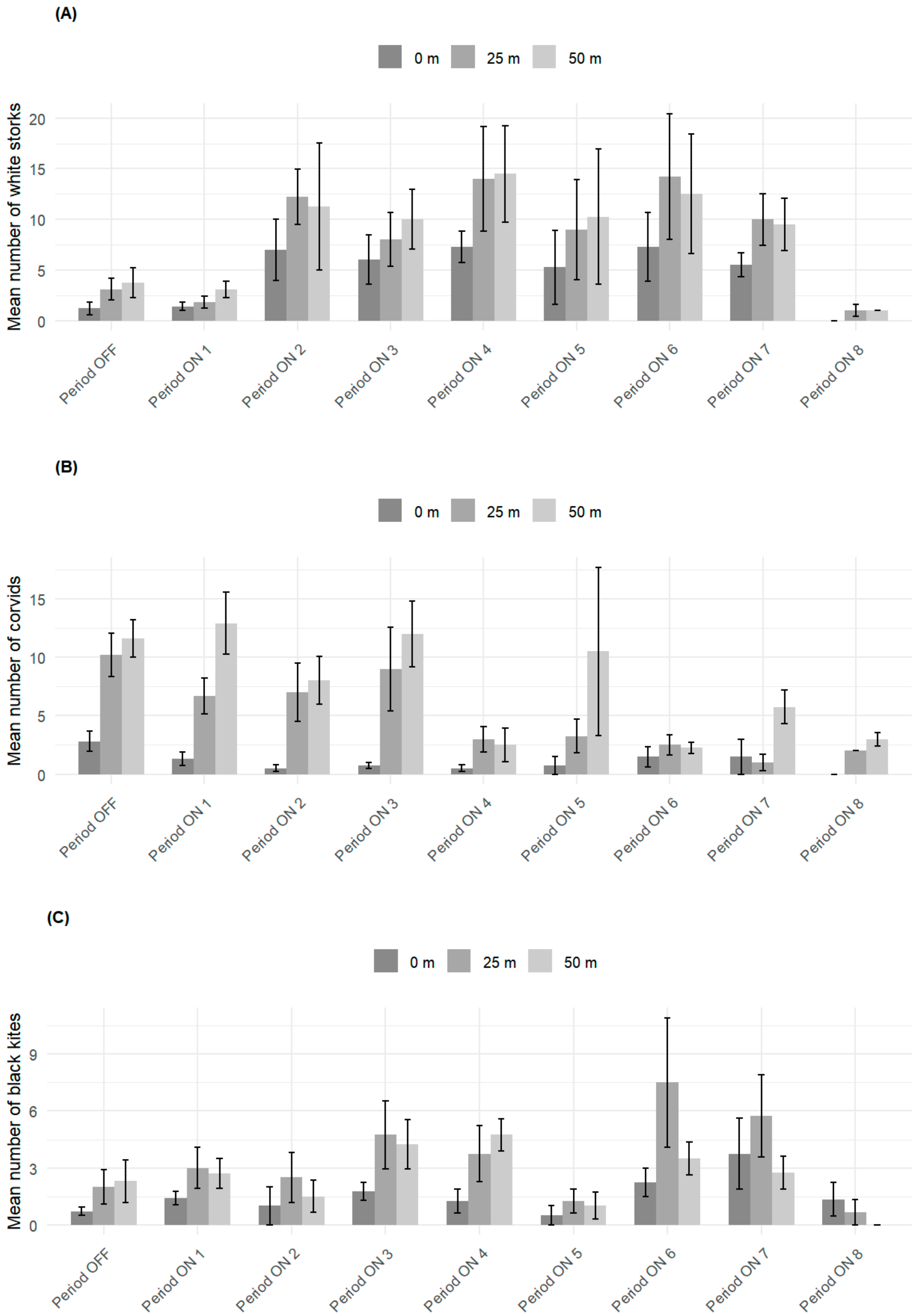

Figure 3. Mean (±S.E.) number of (**A**) white storks, (**B**) corvids, and (**C**) black kites recorded perching or approaching the poles at the distances of 0, 25, 50 m from the deterrent device, during the different periods.

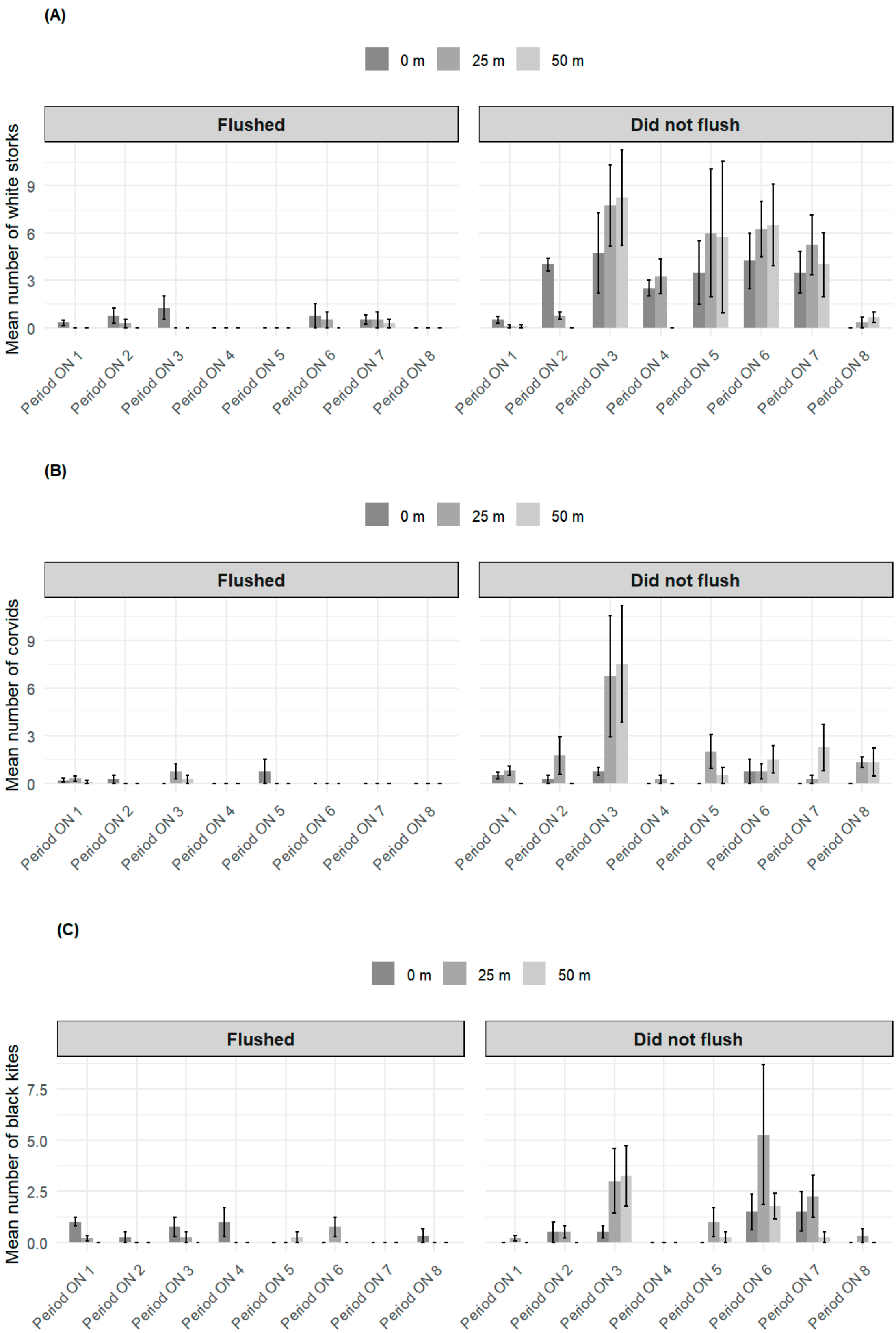

Figure 4. Mean (±S.E.) number of (**A**) white storks, (**B**) corvids, and (**C**) black kites that flushed and did not flush in response to the device sound on the poles 0, 25, 50 m from the deterrent device, during the different periods when the device was switched on.

4. Discussion

Our study evaluated the effectiveness of a deterrent prototype designed to reduce bird use of powerline poles, thereby mitigating the risk of mortality from electrocution and collision.

The deterrent device employed a motion detection system, which was triggered and activated 588 times when birds approached or perched on the pole. The emitted sound effectively flushed 10.6% of the birds either perching or approaching the poles. Specifically, the deterrent device prevented 3.9% of the birds from perching, while 4.1% perched during sound activation and flushed afterwards, and 2.6% were already perched when the sound was activated and then flushed. Considering the birds perching or approaching the pole where the device was installed, 25% were deterred by the sound. However, at distances of 25 m and 50 m, only 5% of the birds were flushed.

The response to the emitted sound varied among the three bird species studied. Black kites were the most reactive species, consistently being the most frequently flushed species at all distances (0 m, 25 m, and 50 m) and showing the lowest perching rate with the sound activated. In contrast, white storks were the least responsive to the deterrent sound. Although the number of white storks increased significantly during the study period, they showed fewer flushing events. This species benefits from landfills for feeding and selecting nesting and breeding sites [29], becoming less sensitive to environmental disturbances as they age [30]. The proportion of corvids perching or approaching the poles decreased significantly over time, with their sensitivity lying between that of black kites and white storks. Corvids are known for their high intelligence, showing strong cognitive and learning abilities [31], which may explain their tendency to avoid the sound over time.

Thus, the effectiveness of our deterrent device varies by species, potentially yielding better results for those who are more sensitive or wary of novel stimuli. These findings align with previous research indicating species-specific variability in response to bird deterrent systems [1]. According to [32,33], white storks and corvids are among the species with the highest mortality rates from electrocution recorded in the Iberian Peninsula, while black kites show lower mortality rates. Birds with larger wingspans, such as white storks, are at a higher risk due to their increased likelihood of contacting powerline components [34]. However, all the studied species face significant concerns because of their perching behavior, often remaining on poles for extended periods. In addition, for gregarious species, the risk is even greater, as close contact between individuals can result in chain reactions, leading to massive electrocution events [34].

The study also evaluated the effect of distance from the deterrent device on bird behavior. We found that the deterrent device was most effective at the central pole (0 m) which hosted the device, with diminishing effects at greater distances. This attenuation of the deterrent effect with distance suggests that the sound levels and sensor range might be insufficient for effective deterrence beyond a certain proximity. However, the lack of accommodation effects over time indicates that the birds did not become less responsive to the deterrent sounds, demonstrating the prototype's consistent effectiveness throughout the study period.

Other innovative sound systems, such as DTBird, have been developed to detect and prevent bird collisions on wind turbines. These systems use real-time bird detection through a camera-based technology that can detect birds at long distances, triggering two audible signals: first, a warning signal when a bird approaches a critical distance, then a stronger dissuasion signal, encouraging the bird to alter its flight path. Several institutes have tested DTBird systems, with pilot results revealing different rates of success: ref. [35] observed avoidance behavior in 88% of cases where the bird was on a collision course, also indicating that this is a viable system for bird detection; ref. [36] reported a 52% successful deterrence rate for the target species (golden eagles), and 30–40% for other raptors, while the detection probability was 63%; ref. [37] found a 20–30% reduction in the likelihood of approaching the rotor-swept zone, increasing to 40% for birds at a higher risk of entering it, with a detection probability of ~65%; ref. [38] recorded a 19% successful deterrent rate and a detection probability of 30.5%; and in [39], only 7% of the birds responded to the warning/dissuasion signals, although the detection probability was higher than 80%. These studies also presented high rates of false-positive detections (30–69%), with higher deterrence and detection probabilities at shorter distances from the wind turbines/for birds closer to wind turbines.

Alternative works with similar systems [40,41] have explored strobe lights combined with audible alarms as warning signals, yet none have shown the results of their effectiveness in preventing bird collisions.

Despite some positive results, we recognize the following limitations in our deterrent device and the experimental design:

(1) The device was effectively triggered by approx. 63% of the overall number of birds perching or approaching the pole where the device was installed. To enhance its efficiency, the sensitivity and range of motion detection should be optimized to detect a higher percentage of approaching birds. Moreover, when transposed to electric poles, the installation of the deterrent device should prioritize those with the highest risk of electrocution [13].
(2) The device was tested using a selection of four randomly alternating sounds, each with a peak intensity of 100 dB. Further research should explore variations in sound types, frequencies, and duration to determine the most effective combination for deterring the greatest number of bird species.
(3) The effectiveness of the device seems to be distance-limited. The low detection range of the infrared sensors restricted the assessment of deterrent effects beyond 12 m, impacting the comprehensiveness of the collected data. In addition, most flushing events occurred on the pole where the deterrent device was installed. The sound intensity reaching the farthest poles was lower and likely insufficient to flush these birds which are already acclimated to frequent sound disturbances, as observed in landfills. Addressing this limitation will require increasing the detection range and sound propagation, as well as covering potential blind areas where the device may currently fail to trigger.
(4) The study was conducted over a short-term period. Extending the field testing period is necessary to assess the long-term effectiveness of the deterrent device and to investigate potential habituation effects over an extended timeline.
(5) The study was limited to one location and did not consider seasonal variations. Expanding the study to include diverse habitats and seasons, potentially hosting different bird species, would ensure a more comprehensive understanding of its effectiveness under varying environmental conditions.
(6) The study lacked a control group of poles without the sound device's effect, which would allow for a more accurate evaluation of variations in the overall number of birds using the landfill during the study period. Some of the individuals that were flushed first perched on the poles while the sound device was active. Although this outcome does contribute to reducing the prolonged exposure of birds to the infrastructure, thus lowering the risk of electrocution, it is insufficient to entirely prevent it.

Based on our results, further refinement of the device's design is necessary to identify the most efficient combination of sounds, frequencies, and durations to maximize bird flushes. Nevertheless, a significant advantage of our device is its adaptability, both in implementing changes and in its easy installation, allowing for straightforward improvements in its effectiveness. In addition, the maintenance of the device is minimal. It was only necessary to charge the battery after each monitoring period, replacing it with a fully charged battery, and to ensure that the battery box remained dry after heavy rain. This device also holds the potential to be integrated with several other infrastructures, including those that pose a threat to birds (e.g., powerlines), those where birds may cause risks to humans (e.g., airports, bridges), and those susceptible to damage by birds (e.g., monuments, public lighting). This versatility makes it a valuable tool for bird conservation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ecologies6010012/s1, Figure S1: GESAMB facilities with high concentrations of medium-/large-sized birds and light poles; Figure S2: Light pole with the perching deterrent prototype; Table S1: Mean (±S.E.) number of birds (white stork, corvids, black kite) recorded perching or approaching the poles at the distances (Dist.) 0, 25, 50 m from the deterrent device and in all poles (total), during the periods; Table S2: Mean (±S.E.) of the number of birds (white stork, corvids, black kite) that flushed and did not flush in response to the device sound in the poles at 0, 25, 50 m from the deterrent device and in all poles (total), during the periods with the device switched on.

Author Contributions: Conceptualization, H.R., N.M.P., A.M. and N.S.; Methodology, H.R.; Formal analysis, J.R.-S.; Investigation, J.R.-S.; Resources, H.R. and N.S.; Data curation, J.R.-S.; Writing—original draft, J.R.-S.; Writing—review & editing, N.M.P., A.M. and N.S.; Project administration, N.S.; Funding acquisition, N.M.P., A.M. and N.S. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and approval were waived for this study, as the research was non-intrusive and only involved bird observations.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article and supplementary material. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Janss, G.F.E. Avian mortality from powerlines: A morphological approach of a species-specific mortality. *Biol. Conserv.* **2000**, *95*, 353–359. [CrossRef]
2. Lehman, R.N.; Kennedy, P.L.; Savidge, J.A. The state of the art in raptor electrocution research: A global review. *Biol. Conserv.* **2007**, *136*, 159–174. [CrossRef]
3. Hernández-Matías, A.; Real, J.; Parés, F.; Pradel, R. Electrocution threatens the viability of populations of the endangered Bonelli's eagle (*Aquila fasciata*) in Southern Europe. *Biol. Conserv.* **2015**, *191*, 110–116. [CrossRef]
4. Sergio, F.; Marchesi, L.; Pedrini, P.; Ferrer, M.; Penteriani, V. Electrocution alters the distribution and density of a top predator, the eagle owl (*Bubo bubo*). *J. Appl. Ecol.* **2004**, *41*, 836–845. [CrossRef]
5. Rubolini, D.; Gustin, M.; Bogliani, G.; Garavaglia, R. Birds and powerlines in Italy: An assessment. *Bird Conserv. Int.* **2005**, *15*, 131–145. [CrossRef]
6. Pérez-García, J.M.; Botella, F.; Sánchez-Zapata, J.A.; Moleón, M. Conserving outside protected areas: Edge effects and avian electrocutions on the periphery of Special Protection Areas. *Bird Conserv. Int.* **2011**, *21*, 296–302. [CrossRef]
7. Angelov, I.; Hashim, I.; Oppel, S. Persistent electrocution mortality of Egyptian Vultures (*Neophron percnopterus*) over 28 years in East Africa. *Bird Conserv. Int.* **2013**, *23*, 1–6. [CrossRef]

8. Bevanger, K. Biological and conservation aspects of bird mortality caused by electricity powerlines: A review. *Biol. Conserv.* **1998**, *86*, 67–76. [CrossRef]
9. Bayle, P. Preventing birds of prey problems at transmission lines in western Europe. *J. Raptor Res.* **1999**, *33*, 43–48.
10. Infante, O.; Peris, S. Bird nesting on electric power supports in northwestern Spain. *Ecol. Eng.* **2003**, *20*, 321–326. [CrossRef]
11. Bevanger, K. Bird interactions with utility structures: Collision and electrocution, causes and mitigation measures. *Ibis* **1994**, *136*, 412–425. [CrossRef]
12. Ferrer, M.; Riva, M.J.; Castroviejo, J. Electrocution of raptors on powerlines in southwestern Spain. *J. Field Ornithol.* **1991**, *62*, 181–190.
13. Mañosa, S. Strategies to identify dangerous electricity pylons for birds. *Biodivers. Conserv.* **2001**, *10*, 1997–2012. [CrossRef]
14. Chevallier, C.; Hernández-Matias, A.; Real, J.; Vincent-Martin, N.; Ravayrol, A.; Besnard, A. Retrofitting of powerlines effectively reduces mortality by electrocution in large birds: An example with the endangered Bonelli's eagle. *J. Appl. Ecol.* **2015**, *52*, 1465–1473. [CrossRef]
15. Janss, G.F.E.; Ferrer, M. Mitigation of raptor electrocution on steel power poles. *Wildl. Soc. Bull.* **1999**, *27*, 263–273.
16. Janss, G.F.E.; Ferrer, M. Avian electrocution mortality in relation to pole design and adjacent habitat in Spain. *Bird Conserv. Int.* **2001**, *11*, 3–12. [CrossRef]
17. Tintó, A.; Real, J.; Mañosa, S. Predicting and correcting electrocution of birds in Mediterranean areas. *J. Wildl. Manag.* **2010**, *74*, 1852–1862. [CrossRef]
18. Kaluga, I.; Sparks, T.H.; Tryjanowski, P. Reducing death by electrocution of the white stork (*Ciconia ciconia*). *Conserv. Lett.* **2011**, *4*, 483–487. [CrossRef]
19. Maricato, L.; Faria, R.; Madeira, V.; Carreira, P.; Almeida, A.T. White storks risk mitigation in high voltage electric distribution networks. *Ecol. Eng.* **2016**, *91*, 212–220. [CrossRef]
20. Jenkins, A.R.; Smallie, J.J.; Diamond, M. Avian collisions with powerlines: A global review of causes and mitigation with a South African perspective. *Bird Conserv. Int.* **2010**, *20*, 263–278. [CrossRef]
21. Barrientos, R.; Alonso, J.C.; Ponce, C.; Palacin, C. Meta-analysis of the effectiveness of marked wire in reducing avian collisions with powerlines. *Conserv. Biol.* **2011**, *25*, 893–903. [CrossRef]
22. Dwyer, J.F.; Harness, R.E.; Gerber, B.D.; Landon, M.A.; Petersen, P.; Austin, D.D.; Woodbridge, B.; Williams, G.E.; Eccleston, D. Power pole density informs spatial prioritization for mitigating avian electrocution. *J. Wildl. Manag.* **2016**, *80*, 634–642. [CrossRef]
23. Mojica, E.K.; Dwyer, J.F.; Harness, R.E.; Williams, G.E.; Woodbridge, B. Review and synthesis of research investigating golden eagle electrocutions. *J. Wildl. Manag.* **2018**, *82*, 495–506. [CrossRef]
24. Dixon, A.; Rahman, L.M.D.; Galtbalt, B.; Bold, B.; Davaasuren, B.; Batbayar, N.; Sugarsaikhan, B. Mitigation techniques to reduce avian electrocution rates. *Wildl. Soc. Bull.* **2019**, *43*, 476–483. [CrossRef]
25. IPMA. Portal do Clima. Instituto Português do Mar e da Atmosfera. Available online: http://portaldoclima.pt/pt/ (accessed on 1 March 2021).
26. Wood, S.N. *Generalized Additive Models: An Introduction with R*; Chapman and Hall/CRC: Boca Raton, FL, USA, 2017.
27. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria. Available online: https://www.R-project.org/ (accessed on 1 March 2021).
28. RStudio Team. *RStudio: Integrated Development for R*; RStudio, Inc.: Boston, MA, USA, 2020. Available online: http://www.rstudio.com/ (accessed on 1 March 2021).
29. Bialas, J.T.; Dylewski, Ł.; Dylik, A.; Janiszewski, T.; Kaługa, I.; Królak, T.; Kruszyk, R.; Pawlukojć, K.; Pestka, Z.; Polakowski, M.; et al. Impact of land cover and landfills on the breeding effect and nest occupancy of the white stork in Poland. *Sci. Rep.* **2021**, *11*, 7279. [CrossRef]
30. Kaminski, P.; Jerzak, L.; Sparks, T.H.; Johnston, A.; Bochenski, M.; Kasprzak, M.; Wiśniewska, E.; Mroczkowski, S.; Tryjanowski, P. Sex and other sources of variation in the haematological parameters of White Stork (*Ciconia ciconia*) chicks. *J. Ornithol.* **2014**, *155*, 307–314. [CrossRef]
31. Emery, N.J. Cognitive ornithology: The evolution of avian intelligence. *Philos. Trans. R. Soc. B* **2006**, *361*, 23–43. [CrossRef] [PubMed]
32. Baquedano, R.; Peris, S.J. Accidentalidad invernal del Busardo Ratonero (B. buteo) en tendidos eléctricos en la Península Ibérica. *Munibe (Ciencias Naturales Natur Zientziak)* **2003**, *54*, 113–120.
33. Infante, S.; Neves, J.; Ministro, J.; Brandão, R. *Estudo Sobre o Impacto das Linhas Eléctricas de Média e Alta Tensão na Avifauna em Portugal*; Final Technical Report; Quercus Associação Nacional de Conservação da Natureza e SPEA Sociedade Portuguesa para o Estudo das Aves: Castelo Branco, Portugal, 2005.
34. Garrido, J.R.; Martín, J. Identificación de tendidos eléctricos peligrosos. In *Manual Para la Protección Legal de la Biodiversidad Para Los Agentes de la Autoridad Ambiental en Andalucía*; Fajardo, I., Martin, J., Eds.; Consejería de Medio Ambiente, Junta de Andalucía: Sevilla, Spain, 2009; pp. 272–295.

35. Litsgård, F.; Eriksson, A.; Wizelius, T.; Säfström, T. DTBird system pilot installation in Sweden. Possibilities for bird monitoring systems around wind farms. Experiences from Sweden's first DTBird installation Tech. rep. Ecocom AB, Kalmar, Sweden. December 2016.
36. Terrill, S.; Howell, J.; Smith, J.; Zirpoli, J.; Wolf, K.; Lindke, K.; Watt, S. *Evaluating a Commercial-Ready Technology for Raptor Detection and Deterrence at a Wind Energy Facility in California*; H.T. Harvey & Associates; American Wind Wildlife Institute (AWWI): Washington, DC, USA, September 2018.
37. Felton, S.K.; Perkins, L.J.; Smith, J.P.; Terrell, S.B. *Evaluating the Effectiveness of a Detection and Deterrent System in Reducing Golden Eagle Fatalities at Operational Wind Facilities*; Final Report DE-EE0007883; Renewable Energy Wildlife Institute (REWI): Washington, DC, USA, May 2024.
38. Hanagasioglu, M.; Aschwanden, J.; Bontadina, F.; Nilsson, M. *Investigation of the Effectiveness of Bat and Bird Detection of the DTBat and DTBird Systems at Calandawind Turbine*; Final Report No. 291031; Swiss Federal Office of Energy (SFOE): Ittigen, Switzerland, May 2015.
39. May, R.; Hamre, Ø.; Vang, R.; Nygård, T. *Evaluation of the DTBird Video-System at the Smøla Wind-Power Plant: Detection Capabilities for Capturing Near-Turbine Avian Behaviour*; NINA Report 910; Norwegian Institute for Nature Research: Trondheim, Norway, 2012.
40. Gradolewski, D.; Dziak, D.; Martynow, M.; Kaniecki, D.; Szurlej-Kielanska, A.; Jaworski, A.; Kulesza, W.J. Comprehensive Bird Preservation at Wind Farms. *Sensors* **2021**, *21*, 267. [CrossRef] [PubMed]
41. Gullipalli, R.; Golla, K.K. Arduino-Based Radio Technology System for Bird Protection: Wind Farm Application Approach. Bachelor's Thesis, Blekinge Institute of Technology, Karlskrona, Sweden, 2020.