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EXPERIMENTALLY BROADCASTED WIND-TURBINE SOUND DRASTICALLY ALTERS SONGBIRDS' HABITAT SELECTION AND VOCAL COMMUNICATION IN A NATURAL ENVIRONMENT

Yael Lehnardt[1*]   **Tom Klein**[2]   **Jesse R. Barber**[3]   **Oded Berger-Tal**[1]

[1] Mitrani Department of Desert Studies, The Jacob Blaustein Institutes for Desert Research, Ben Gurion University, Israel

[2] State University of New York College of Environmental Science and Forestry, USA

[3] Department of Biological Sciences, Boise State University, Idaho, USA

ABSTRACT*

The sound of wind turbines is a potential threat to songbirds, who use vocal communication to transfer information and rely on acoustic cues from the environment. Previous studies have shown decreased bird density around wind-farms, but the exact causes for this decline have not yet been fully recognized. We investigated the effects of wind-turbine sound on songbird populations by deploying a "Phantom Turbine": broadcasting wind-turbine sound (102dB) at a site without actual turbines. We conducted the experiment in cycles of three stages: 'before', 'noise-treatment', and 'after'. We monitored birds' abundance using mist-netting and recorded freely-flying birds' communication and background noise levels using calibrated automated recorders. Wind turbine noise caused a significant decrease of approximately 45% in the mean number of Sardinian Warblers (*Corruca melanocephala momus*) and a significant reduction in the number of detected calls compared to the control stages. The broadcasted sound overlapped birds' known hearing range and measured vocalization frequency range, providing possible explanations for birds' avoidance. These findings provide evidence of a strong negative impact of wind-turbine sound on habitat selection and vocal communication in a songbird population, emphasizing the need to consider noise impacts when planning wind farms or other noisy infrastructures in natural environments.

Keywords: *noise pollution. wind farm, animal behavior, Sardinian warbler, HIREC*

1. INTRODUCTION

The natural acoustic environment, also known as the soundscape, is composed of a combination of geophonic and biophonic sounds [1]. Animals use acoustic information from their surroundings to assess habitat quality and resource distribution [1], [2]. Accordingly, measuring the acoustic features of a landscape can be a valuable indicator of habitat quality and functionality as it is perceived by wildlife [3], [4]. In recent centuries, a new type of sound was introduced to the natural soundscape: anthropophonic sounds. This pervasive and important anthropogenic element is causing extensive habitat degradation and is commonly termed 'noise pollution': an intense, widespread pollutant that affects many species worldwide, even in supposed refuges such as national parks [5], [6].

Wind turbines, despite their recognized environmental advantages, are emerging as a prominent contributor to noise pollution [7], [8]. Specifically, the noise generated by wind turbines significantly alters the natural soundscape by introducing airborne broadband sound [7] that falls within the hearing range of numerous animal species, including a majority of bird species [9], [10]. This is of significant concern because wind farms are typically situated in open elevated habitats, deliberately chosen to be distant from human settlements and other man-made structures. Consequently, these sites experience minimal anthropogenic noise pollution before wind turbines are installed.

Although numerous studies have investigated bird mortality resulting from collisions with turbines, there is a notable scarcity of research examining bird avoidance of wind farms. Furthermore, studies investigating the specific effects of turbine-generated noise on birds are particularly rare [11]. The limited available literature indicates that wind-turbine noise has an impact on bird behavior, specifically influencing habitat utilization and vocal communication [8], [11]–[13]. As previously mentioned, the mechanisms by which wind-turbines affect bird

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behavior and distribution are largely unknown, most likely due to the difficulty in separating the many confounding effects created by the wind-turbines including direct mortality, noise, wind, and pulsing lights [14]. Given the aforementioned limitation and the fact that the magnitude of noise created by a wind-turbine can reach dozens of decibels at distances up to one kilometer from a turbine, the effects of wind-turbine noise on the movement and habitat selection of birds have been highlighted as an important knowledge gap in our understanding of wind-turbine-wildlife interactions [15], [16].

Changes in birds' vocal characteristics in response to anthropogenic noise may emphasize their reliance on acoustic communication (rather than visual, tactile etc.) as well as reflect their ability to sense and adjust to an altered acoustic environment instead of avoiding it entirely. Because of that, the study of vocalizations might allow us to glean information regarding the way birds cope with Human-induced rapid environmental changes. Examples for changes in communication due to elevated background noise can be found in a growing number of studies, mainly from laboratory experiments but also from urban environments or breeding sites placed next to noise sources (e.g. [11], [17], [18]). Vocal adjustments include changing the amplitude, the frequency, or the temporal structure of the call [19 but see 20]. Another possibility, which is mainly relevant for highly predictable and persistent sources of noise, is altering the timing of the call delivery [21- 22, but see 23]. Yet, the ability to change vocal signals does not necessarily mean it is enough to overcome negative noise impacts [24]. If the additive effects of these changes in vocalizations reach a critical threshold, they may negatively impact the efficiency of birds' social learning and the reliability of data transmission [25]. These changes may therefore have consequences on the survival and overall fitness of the calling individuals [24], [26].

Most studies on the behavioral responses, and specifically of vocal adjustments, of terrestrial animals to noise pollution were conducted in either North America or Europe during the breeding season, where animals use acoustic signals for breeding-related behaviors [27], [28]. Very few studies looked at the effects of noise pollution on non-breeding calls outside the breeding season [e.g. 29]. Specifically, studies on altered communication of birds during post-breeding dispersal are scarce and are therefore of great importance for our understanding of noise pollution impacts on wildlife.

In this study, we tested the effects of wind-turbine noise on songbirds' vocalizations by creating a 'phantom wind turbine' (*sensu* McClure at al. [30]; 'phantom-road' experiment): an experimental manipulation that replicates the sounds of a wind turbine in the absence of other cues that are often associated with these structures (e.g., visual or tactile cues). Accordingly, we broadcasted wind-turbine noise and measured both the soundscape and the vocal communication of the Sardinian Warbler (*Sylvia melanocephala momus*) before, during, and after the noise treatment.

2. METHODS

We explored how artificially broadcasted wind turbine noise affected the vocal communication of a songbird during post-breeding dispersal in a nature reserve. To do so, we measured the acoustic environment repeatedly, in three phases: before noise-treatment, during noise-treatment, and after it (hereafter: 'before, 'noise-treatment', and 'after'). The duration of every phase was 48 hours and thus every full repeat of the experiment took six days, allowing us to exclude the weekend and keep the natural soundscape at the site as homogenous as possible.

2.1 Study site and focal species

By repeatedly turning the "phantom wind-turbine" on and off according to the experimental design, and by verifying that the response recorded was of a different cohort of birds every round (using bird-ringing in parallel with acoustic monitoring), we were able to conduct the experiment at a single site, avoiding the impact of among-site variation when the short autumn season allows a limited number of repeats. The study was conducted in the Horesh Adulam Nature Reserve in central Israel, which is a generally homogenous Mediterranean Maquis habitat. The reserve is located more than 1.5 km from a small village and is enclosed by three minor roads, making it relatively quiet and ideal for sound recordings and manipulations. The focal species of this study is a resident population of the species Sardinian Warbler, Corruca melanocephala momus [31], [32]. It is one of the most common species at this site during its post-breeding dispersal and vocalizes year-round.

2.2 Phantom wind turbine

Wind-turbine noise arises from various mechanisms, with the strongest being the flow of air across the turbine blades. This results a broadband (up to about 5kHz but can reach also higher frequencies in some cases) continuous yet fluctuating sound, strongly affected by wind speed. As the blades rotate, they generate distinctive aerodynamic swooshes and blade pass noise, contributing to the unique auditory signature of wind turbines [7], [33], [34]. Commercial speakers can replicate such noise almost

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accurately, closely resembling the original sounds except for the omission of infra-sound impact, which was not within the scope of this study. To create the phantom turbine, we placed a speaker (Soundboks2, 40-20,000Hz, Soundboks, China) approximately 2 m off the ground; this height is above the main vegetation level, which allows good sound propagation and is also relevant to target foraging songbirds inside vegetation. Using this speaker, we were able to broadcast wind-turbine noise within the frequency and amplitude range that is pertinent to both avian and human auditory systems [10].

On each treatment day, wind-turbine noise was broadcasted at 102 dB(A) measured for 60 seconds at a distance of 1 meter from the speaker. The noise was broadcasted for the typical operation duration of wind-turbines in the region and covered the activity hours of songbirds - one and a half hours before sunrise (~45 min before first light) until one hour after sunset. The WAV recording of wind-turbine noise was kindly provided by Timothy Van Renterghem (for recording procedure, see [35]).

2.3 Acoustic monitoring

To measure and depict the impact of the phantom wind turbine on the acoustic environment, we continuously recorded the soundscape throughout the study site during all experimental phases. The acoustic data collection followed the guidelines described by Merchant et al. [36] and McKenna et al. [37]. Accordingly, we used calibrated recorders (sensu Mennitt and Fristrup [38]) to provide absolute background-noise levels and not only relative measurements. The Acoustic Recording Units (ARU; Roland R05 audio recorder) recorded continuously (24 hours a day for the duration of each entire experimental repeat) at a sampling rate of 48 kHz. The ARUs were deployed inside a wind-protecting coating within Palestine Oaks, Quercus calliprinos, 1.5 meters above the ground to represent the acoustic environment as experienced by foraging songbirds at the site. Simultaneously, Swift recorders (developed by the K. Lisa Yang Center for Conservation Bioacoustics at the Cornell Lab of Ornithology) were set in the exact same location to provide high-quality WAV recordings, to capture vocal communication of songbirds. Each recording was 20 min long. In this work, we focused on the recordings from the nearest recorder placed downwind from the phantom wind

turbine (70 m), where sound levels were most impacted by the noise treatment.

To account for seasonal changes, we aligned the recordings based on first light rather than the clock. We note that the peak of warblers' vocal communication occurred in recordings taken 1-4 hours after first light, which may correspond to foraging behavior. In contrast, the peak of wind turbine noise levels occurred 0-3 hours after first light, likely due to weather conditions. Therefore, we focused our analysis on recordings made between 0-3 hours after first light. In addition, to ensure unbiased and appropriate analysis, we applied the following criteria to select recordings: both R05 and Swift recorders were active and functioning properly, did not coincide with mist-net checks (human presence), and wind speed did not exceed 8 m/s (to avoid artifacts produced by high-speed winds [39]). An equal number of recordings were taken from each experimental phase, for each 20-minute window. In total, 120 recordings 20 minutes long were selected, 40 per experimental phase.

2.4 Calls detection and performance assessment

The detection of the Sardinian Warbler calls was done using 'R' version 4.2.2 [40] , the 'Rraven' open source package [41] and Band-Limited Energy Detector (BLED) in RavenPro version 1.5 [42]. It is a non-specific detector, searching for events where energy in specific frequency band exceeds a specified threshold [42]. The detector was bound to a frequency range that minimally overlapped with the experimental background noise (i.e., above 4.5 kHz) to guarantee similar detection probability and accurate comparison of bio-acoustical measurements between treatment phases [20], [43]. To assess the performance of the custom-made BLED, each detection was manually verified and categorized into TP (true positive) or FP (false positive). Verification was done by a single person (TK) who did not participate in field data collection and was unaware of the experimental settings to assure blinded processing. He used consistent settings of the spectrogram in Raven Pro and combined auditory verification when needed. In questionable detections, he consulted with a bird expert (YL). FPs were used only to calculate recognizer performance metrics and otherwise removed. Additionally, to check for missed detections, the same person marked all missed detections in the last minute of the recording. This was done in 50% of the files from each 20-minute window,

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chosen randomly [40], totaling 66 files at the focal recording site. Files from several locations and experimental phases were processed simultaneously and organized by another person (YL).

The vocalizations produced by the Sardinian warbler exhibit a consistent pattern characterized by a sequence of two syllables (sometimes one to three; referred to as 'clicks', as shown in Fig. 1.A.) that are iteratively repeated to form a variably-long 'rattle' [44]. These 'rattles' of 'clicks' are then repeated over time (Fig. 1.B). To avoid pseudo-replication and prevent biases from possible unbalanced detection probability between treatments, each rattle was counted only once (i.e., not counting repeating clicks from each rattle). To identify time gaps within and between rattles, 125 validated TP detections (44 from control phases, 81 from 'noise-treatment') were manually checked (considering also false negatives – i.e., missed clicks) to conclude if they are part of the same or different rattles. Finally, a threshold of 0.27 s was determined as the maximum gap between detected clicks within the same rattle (Table 1). Accordingly, instances where calls occurred less than 0.27 seconds apart, were considered as a single rattle.

Table 1. Time gaps between 'click' syllables within and between rattles based on 125 verified TP calls.

	Within rattle	Between rattles
Min (s)	0.004	3.4
Mean (s)	0.07	42.3
Max (s)	0.27	176.9

2.5 Data Analysis

All analyses were done using 'R' version 4.2.2 [40]. The following recognizer performance metrics were calculated: FN rate ("missed"), FP rate, and recall ("sensitivity"; "scanning comprehensiveness") [45]. Notably, no FPs were found in any of the experimental phases in the data used for searching missed detections. Statistical analysis was performed using Generalized Linear Models (GLZ) with a negative binomial distribution, as count data exhibited overdispersion. The models included (1) the number of calls or (2) the number of rattles as the explained variable. Explanatory variables included the experimental phase (categorical) and time of day (categorical; hours relative to first light and not clock). To conclude whether the treatment phase significantly impacted the number of calls\rattles, each model was compared to a null model (i.e., same model without the treatment phase) using likelihood ratio test. The

results of the GLZ are reported only when the model with the treatment phase was significantly better than the null model [46].
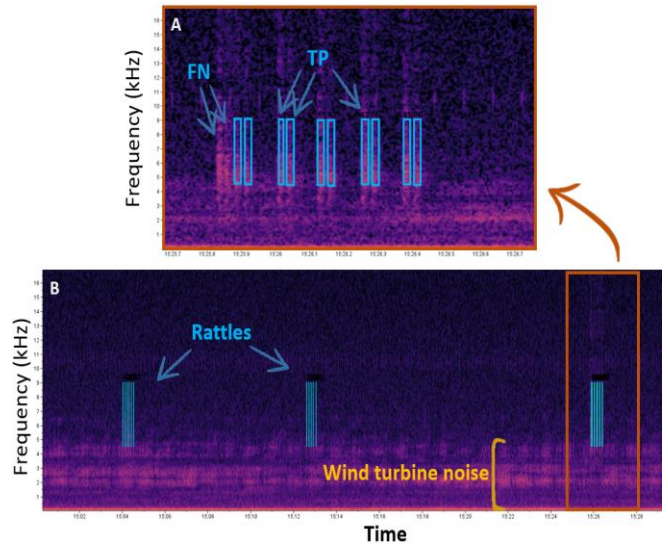

Figure 1. A. a spectrogram of detected and verified calls (in blue rectangles; TP) of Sardinian Warbler (*Curruca melanocephala momus*), showing a classic pattern of two 'click' syllables repeated to create a classic 'rattle' composed of 6 double 'clicks'. Two calls missed by the automatic identifier (FN) are seen on the left. **B.** Several rattles over a longer timeframe (x-axis), the last is enlarged in A (red rectangle). Note that there is only partial overlap in the frequencies (y-axis) of the calls and the wind turbine noise playback (orange marking; the lower half of the spectrogram) allowing proper automated detection of the calls using Band-Limited Energy Detector in RavenPro.

3. RESULTS

A total of 8,074 signals were detected using the Band-Limited Energy Detector in RavenPro in 120 recordings of 20 minutes from the downwind recorder nearest (70 m) to the phantom wind turbine. Of these signals, 5,253 were confirmed as true positive (TP; Sardinian warblers' vocalizations) and 2,821 classified as false positive (FP) and removed from all statistical models.

3.1 Automated detection

A sub-sample of 66 20-minute recordings were randomly selected, representing 55% of the recordings and 2.75% of the recorded time. The last minute of each of these files was then examined to identify FP detections. Altogether, 447

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FNs were identified, a high number compared to 119 TP automatically detected in the same sub-sample.

Table 2. Number of FN (missed) calls identified in the sub-sampled data (the last minute of 66 recordings), number of TP and FP categorized detections, and calculated recognizer performance metrics [45].

Experimental phase	FN	TP	FP	FN rate	FP rate	Recall
Before	185	23	0	0.89	0	0.11
Noise-treatment	8	7	0	0.53	0	0.47
After	254	89	0	0.74	0	0.26

3.2 Sardinian Warbler vocal response to wind turbine noise

Noise-treatment had a significant negative effect on the number of calls of Sardinian Warbler ('before': 61.0 ± 54.9 Mean ± SD (here and throughout the text); 'noise-treatment': 11.6 ± 19.8; 'after': 61.3 ± 58.0; likelihood ratio test: $\chi^2_{(df=2)}$= 24.17, p<0.001; GLMM Poisson distribution: $df_{residual}$= 88, Z value= 5.17 and 5.33, for comparison of 'noise-treatment' with 'before' and with 'after' phases respectively, p<0.001 for both comparisons; Table 3).

Table 3. Sardinian Warbler calls and rattles in relation to broadcasted wind turbine noise in three experimental phases ('before', 'noise-treatment', and 'after'). Bold depicts significantly affected vocal features.

Experimental phase	TP	FP	Calls (TP) per recording	# Rattles	Rattles (TP) per recording
Before	2440	238	**61.0 ± 54.9**	514	**12.8 ± 10.3**
Noise-treatment	465	2157	**11.6 ± 19.8**	117	**2.92 ± 4.45**
After	2452	457	**61.3 ± 58.0**	521	**13.0 ± 11.1**

Similarly, the number of rattles was significantly lower during noise-treatment ('before': 12.8 ± 10.3; 'noise-treatment': 2.92 ± 4.45; 'after': 13.0 ± 11.1; likelihood ratio test: $\chi^2_{(df=2)}$= 42.04, p<0.001; GLMM Poisson distribution: $df_{residual}$= 114, Z value= 6.67 and 6.71, for comparison of 'noise-treatment' with 'before' and 'after' phases respectively, p<0.001 for both comparisons; Table 3). For the number of calls per rattle, the addition of experimental phases to the model only marginally improved it compared to the null model ('before': 4.75 ± 3.89; 'noise-treatment': 3.97 ± 3.01; 'after': 4.71 ± 4.09; likelihood ratio test: $\chi^2_{(df=2)}$= 5.32, p=0.07); therefore, we do not present the model results looking into the effect of 'noise-treatment' on this feature of vocal communication.

4. DISCUSSION

The impact of anthropogenic noise on wildlife vocalizations has become an increasingly important topic in ecological research, with only limited work on vocalizations during the non-breeding seasons [27], [29]. In this study, we aimed to explore the effects of experimentally broadcasted wind turbine noise on the vocal behavior of freely dispersing Sardinian Warblers during the post-breeding season. To achieve our goal, we harnessed existing programs and methodologies and created a custom-made detector to speed up the task [42]. We found that Sardinian Warblers vocalize frequently in the non-breeding season, and that the rate of calling was affected by time of day and by experimentally added noise pollution. Warblers produced a significantly lower number of rattles during the 'noise-treatment', without substantially changing the number of 'click' syllables per rattle. This is also translated to a significant decrease in the number of calls, however this may be a problematic metric if the decision whether to call or not is taken at a rattle level and the rattle duration is then fixed. The high variance in the number of syllables per rattle (ranging 1-50 with a median of 7) suggests this is flexible, but it may be due, at least in part, to inconsistent detection success. Our findings highlight the negative impact of noise pollution on the vocal behavior of the Sardinian Warbler as detected at the population level.

4.1 Automated detection

The reliability of the results obtained from the automated recognizer can be assessed using performance metrics [45]. Importantly, the performance metrics support the use of the detected calls after eliminating false positives, as no bias in detection probability was found between the 'noise-treatment' and control phases (Table 2). Albeit, it is important to note that the number of false positives was much higher during the noise-treatment phase (Table 3), indicating the need for precise manual verification when performing acoustic sampling in noise-polluted environments. Moreover, these metrics indicate

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that the lower number of detections during the 'noise-treatment' phase compared to 'before' and 'after' (as shown in section 4.2) was due to fewer calls being emitted and not reduced detection success. This conclusion is supported by the fact that the 'noise-treatment' phase had the lowest false negative rate (i.e., "missed" calls) and the highest recall (i.e., "sensitivity" or "scanning comprehensiveness") value (Table 2).

We note a high proportion of missed calls (53%-89%; Table 2). The higher levels in the control phases compared to 'noise-treatment' may result from the deficient number of calls in the 'noise-treatment' phase rather than an increased sensitivity of the detector when noise pollution is present. Relevantly, the FN rate and recall values varied between the control phases. The differences between the two control phases, and the lack of FPs in this sub-sampled data, suggest that a larger portion of the data should be scanned in future studies (>2.75%) to achieve higher accuracy in the performance metrics. Agreement between controls potentially implies that sampled data reached a satisfactory level.

4.2 Sardinian Warbler response to wind turbine noise

Our wind-turbine noise treatment has led to a reduction of 45% in the number of Sardinian warblers at our field site [47]. Such a reduction in the number of individuals at a site can affect the overall rate of vocal communication at that site in several ways: [48], [49]: (I) Vocal communication may increase due to behavioral compensation - the remaining individuals at the site may increase vocal communication rate [50], as they attempt to effectively communicate with individuals that are now more distant. (II) Vocal communication may stay proportional to the number of individuals at the site – in cases where individuals are displaced regardless of vocal behavior, the rate of calls may decrease proportionally to the decrease in individuals [48]; (III) Vocal communication may decrease – the remaining individuals may vocalize less, in response to a reduction in competition over resources or reflecting the vocal communication strategy of the individuals that choose to remain in a noisy area.

In parallel to the possible response to the reduction in population density, individual birds may alter their vocal communication rate in response to the noise pollution itself. Theoretically, they may exhibit one of three potential scenarios: (I) Increase the rate of information transfer through vocal communication to overcome the reduction in information dissemination caused by, for example, partial energetic masking [51]. This may be achieved through an increase in the number of 'clicks' within a rattle or the number of rattles; (II) maintaining the same vocal communication rate if the information is still disseminated satisfactorily or if they fail to notice\overcome the negative impacts of noise; or (III) decrease the rate of vocal communication as a result of a shift to information dissemination based on other senses (such as visual displays and gestures) due to the difficulty of overcoming noise levels. A reduction in vocal communication rate can also stem from other noise impacts such as increased stress or distraction [52], [53].

Our results, that showed a clear reduction in the number of rattles and calls of the Sardinian warblers in the face of noise pollution, suggests that the exposure to noise pollution and population decline did not result in an increase in vocal communication efforts in this species, at least not at the population or site level. However, we cannot yet verify this at the individual level. Further research is needed to disentangle the complex impact of noise on deterring songbirds and determine whether remaining individuals alter their vocal communication patterns in response to density reduction or to the noise itself, if at all.

The main biological question remains: why did the Sardinian Warblers exhibit such a strong behavioral response to the broadcasted wind turbine noise? An essential part of the answer likely lies in the fact that these birds can hear sounds within this range of amplitudes and frequencies [10]. Loud "swooshing" sounds may disrupt birds by causing various non-mutually exclusive effects, such as annoyance, distraction, and masking [19], [52], [54], leading to displacement and potential conservation concerns. Another explanation arises from birds' significant investment of time and energy in vocalizing during the non-breeding season, which may indicate this behavior's underlying importance. The vocalization frequency range partially overlaps with the wind turbine noise frequency range, leading to the energetic masking of the lower frequencies of the call (Fig. 1.A.). Previous studies on other bird species have demonstrated that lower frequencies are critical and carry important information [55], [56]. Although we do not fully understand the function of the calls produced during this time of year, individuals who vocalize may have left the site because they cannot communicate properly. Further research is necessary to determine the precise mechanism underlying the observed reduction in Sardinian Warbler calls in response to wind turbine noise exposure.

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REFERENCES

[1] B. C. Pijanowski, L. J. Villanueva-Rivera, S. L. Dumyahn, A. Farina, B. L. Krause, B. M. Napoletano, S. H. Gage, and N. Pieretti, *BioScience*, **2011**, DOI:10.1525/bio.2011.61.3.6.

[2] A. Farina, E. Lattanzi, R. Malavasi, N. Pieretti, and L. Piccioli, *Landscape Ecology*, **2011**.

[3] A. Gasc, D. Francomano, J. B. Dunning, and B. C. Pijanowski, *The Auk*, **2017**, DOI:10.1642/AUK-16-124.1.

[4] A. Gasc, B. L. Gottesman, D. Francomano, J. Jung, M. Durham, J. Mateljak, and B. C. Pijanowski, *Landscape Ecology*, **2018**.

[5] J. P. Swaddle, C. D. Francis, J. R. Barber, C. B. Cooper, C. C. M. Kyba, D. M. Dominoni, G. Shannon, E. Aschehoug, S. E. Goodwin, A. Y. Kawahara, D. Luther, K. Spoelstra, M. Voss, and T. Longcore, *Trends in Ecology and Evolution*, **2015**, DOI:10.1016/j.tree.2015.06.009.

[6] R. T. Buxton, M. F. McKenna, D. Mennitt, K. Fristrup, K. Crooks, L. Angeloni, and G. Wittemyer, *Science*, **2017**.

[7] K. Dai, A. Bergot, C. Liang, W.-N. Xiang, and Z. Huang, *Renewable Energy*, **2015**.

[8] M. C. Zwart, J. C. Dunn, P. J. K. McGowan, and M. J. Whittingham, *Behavioral Ecology*, **2016**, DOI:10.1093/beheco/arv128.

[9] R. J. Dooling, B. Lohr, and M. L. Dent, "Hearing in Birds and Reptiles," Comparative Hearing: Birds and Reptiles. 308–359, 2000.

[10] R. Dooling, "Avian Hearing and the Avoidance of Wind Turbines." 2002.

[11] P. Szymański, K. Deoniziak, K. Łosak, and T. S. Osiejuk, *Ibis*, **2017**, DOI:10.1111/ibi.12514.

[12] C. E. Whalen, M. B. Brown, J. McGee, L. A. Powell, and E. J. Walsh, *Ethology*, **2019**.

[13] J. Gómez-Catasús, A. Barrero, D. Llusia, C. Iglesias-Merchan, and J. Traba, *Environmental Pollution*, **2022**, DOI:10.1016/j.envpol.2022.119144.

[14] J. A. Smith and J. F. Dwyer, *Condor*, **2016**, DOI:10.1650/CONDOR-15-61.1.

[15] M. C. Zwart, A. J. McKenzie, J. Minderman, and M. J. Whittingham, "Conflicts between birds and on-shore wind farms," Problematic Wildlife: A Cross-Disciplinary Approach. 489–504, 2015.

[16] R. May, A. B. Gill, K. Johann, R. H. W. Langston, et al., "Future Research Directions to Reconcile Wind Turbine–Wildlife Interactions," Wind Energy and Wildlife Interactions. 255–276, 2017.

[17] C. E. Whalen, M. B. Brown, J. McGee, L. A. Powell, and E. J. Walsh, *The Condor*, **2018**, DOI:10.1650/CONDOR-17-56.1.

[18] K. E. Gentry, E. P. Derryberry, R. M. Danner, J. E. Danner, and D. A. Luther, *Ecosphere*, **2017**, DOI:10.1002/ecs2.1916.

[19] C. P. Ortega, *Ornithological Monographs*, **2018**, DOI:10.1525/om.2012.74.1.6.6.

[20] H. Brumm, S. A. Zollinger, P. T. Niemelä, and P. Sprau, *Methods in Ecology and Evolution*, **2017**.

[21] D. Gil, M. Honarmand, J. Pascual, E. Pérez-Mena, and C. Macías Garcia, *Behavioral Ecology*, **2015**.

[22] D. M. Dominoni, S. Greif, E. Nemeth, and H. Brumm, *Ecology and Evolution*, **2016**, DOI:10.1002/ece3.2357.

[23] D. S. Proppe and E. Finch, *Journal of Ecoacoustics*, **2017**, DOI:10.22261/JEA.TLP16D.

[24] E. Nemeth and H. Brumm, *American Naturalist*, **2010**, DOI:10.1086/656275.

[25] W. Halfwerk, L. J. M. Holleman, CKate. M. Lessells, and H. Slabbekoorn, *Journal of Applied Ecology*, **2011**.

[26] O. Berger-Tal and D. Saltz, in *"Conservation Behavior: Applying Behavioral Ecology to Wildlife Conservation and Management;"* O. Berger-Tal and D. Saltz, Eds.; Cambridge University Press, Cambridge, UK, **2016**.

[27] B. B. M. Wong and H. Lowry, *Behavioral Ecology*, **2016**, DOI:10.1093/beheco/arw102.

[28] G. Shannon, M. F. McKenna, L. M. Angeloni, K. R. Crooks, K. M. Fristrup, E. Brown, K. A. Warner, M. D. Nelson, C. White, J. Briggs, S. McFarland, and G. Wittemyer, *Biological Reviews*, **2016**, DOI:10.1111/brv.12207.

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[29] A. I. Oden, M. Bomberger Brown, M. E. Burbach, J. R. Brandle, and J. E. Quinn, *Ethology*, **2015**, DOI:10.1111/eth.12360.

[30] C. J. W. McClure, H. E. Ware, J. Carlisle, G. Kaltenecker, and J. R. Barber, *Proceedings of the Royal Society B: Biological Sciences*, **2013**, DOI:10.1098/rspb.2013.2290.

[31] H. Shirihai, E. Dovrat, D. A. Christie, and A. Harris, in *"The birds of Israel;"* London: Academic Press., **1996**.

[32] H. Shirihai, G. Gargallo, and A. J. Helbig, in *"Sylvia warblers: identification, taxonomy and phylogeny of the genus Sylvia.;"* A&C Black, **2001**.

[33] G. P. van den Berg, *Journal of Low Frequency Noise, Vibration and Active Control*, **2005**.

[34] A. L. Rogers, J. F. Manwell, and S. Wright, "Wind Turbine Acoustic Noise." Renewable Energy Research Laboratory Department of Mechanical and Industrial Engineering University of Massachusetts, USA, 2006.

[35] T. Van Renterghem, A. Bockstael, V. De Weirt, and D. Botteldooren, *Science of the Total Environment*, **2013**.

[36] N. D. Merchant, K. M. Fristrup, M. P. Johnson, P. L. Tyack, M. J. Witt, P. Blondel, and S. E. Parks, *Methods in Ecology and Evolution*, **2015**, DOI:10.1111/2041-210X.12330.

[37] M. F. McKenna, G. Shannon, and K. Fristrup, *Endangered Species Research*, **2016**, DOI:10.3354/esr00760.

[38] D. J. Mennitt and K. M. Fristrup, *Applied Acoustics*, **2012**, DOI:10.1016/j.apacoust.2012.05.006.

[39] "Acoustical Monitoring training manual." Division, National Park Service U.S. Department of the Interior Natural Sounds and Night Skies, Fort Collins, Colorado, 145–155, 2013.

[40] R Core Team, "R: A language and environment for statistical computing." R Foundation for Statistical Computing, Vienna, Austria, 2022.

[41] M. Araya-Salas, **2017**.

[42] K. Lisa Yang Center for Conservation Bioacoustics at the Cornell Lab of Ornithology, "Raven Pro: Interactive Sound Analysis Software." Ithaca, NY: The Cornell Lab of Ornithology, 2023.

[43] A. A. Ríos-Chelén, A. N. Mcdonald, A. Berger, A. C. Perry, A. H. Krakauer, and G. L. Patricelli, *Behavioral Ecology and Sociobiology*, **2017**, DOI:10.1007/s00265-016-2243-7.

[44] L. Svensson, K. Mullarney, and D. Zetterström, in *"Collins Bird Guide;"* HarperCollins, , **2010**; 2nd Edition.

[45] E. C. Knight, K. C. Hannah, G. J. Foley, C. D. Scott, R. M. Brigham, and E. Bayne, *Avian Conservation and Ecology*, **2017**.

[46] A. Zuur, E. N. Ieno, N. Walker, A. A. Saveliev, and G. M. Smith, in *"Mixed effects models and extensions in ecology with R;"* R. Springer Science & Business Media, **2009**.

[47] Y. Lehnardt, J. R. Barber, and O. Berger-Tal, **in revision**.

[48] S. Oppel, S. Hervias, N. Oliveira, T. Pipa, C. Silva, P. Geraldes, M. Goh, E. Immler, and M. McKown, *Nature Conservation*, **2014**.

[49] C. Pérez-Granados, G. Bota, D. Giralt, A. Barrero, J. Gómez-Catasús, D. Bustillo-De La Rosa, and J. Traba, *Ibis*, **2019**.

[50] H. Brumm and P. J. B. Slater, *Behav Ecol Sociobiol*, **2006**.

[51] P. Rosa and N. Koper, *Ecosphere*, **2018**, DOI:10.1002/ecs2.2127.

[52] D. M. Dominoni, W. Halfwerk, E. Baird, R. T. Buxton, E. Fernández-Juricic, K. M. Fristrup, M. F. McKenna, D. J. Mennitt, E. K. Perkin, B. M. Seymoure, D. C. Stoner, J. B. Tennessen, C. A. Toth, L. P. Tyrrell, A. Wilson, C. D. Francis, N. H. Carter, and J. R. Barber, *Nature Ecology & Evolution*, **2020**.

[53] C. R. Kight and J. P. Swaddle, *Integrative and Comparative Biology*, **2015**.

[54] C. R. Kight and J. P. Swaddle, *Ecology Letters*, **2011**, DOI:10.1111/j.1461-0248.2011.01664.x.

[55] W. Halfwerk, S. Bot, J. Buikx, M. van der Velde, J. Komdeur, C. ten Cate, and H. Slabbekoorn, *Proceedings of the National Academy of Sciences*, **2011**, DOI:10.1073/pnas.1109091108.

[56] D. Gil and H. Brumm, in *"Avian Urban Ecology;"* OUP Oxford, , **2014**.

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