EVALUATING THE USE OF ACOUSTIC WARNING SIGNALS TO REDUCE AVIAN COLLISION RISK

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Abstract

Bird populations have declined sharply in recent years. Collisions with humanmade structures are responsible for a significant portion of this avian mortality, threatening potential ecological consequences and financial burdens to a variety of industries. Acoustic warning signals can be used to alert birds to obstacles in their flight paths in order to mitigate collisions, but these signals should be tailored to the sensory ecology of birds in flight. I evaluated the ability of four different sound signals to elicit collision-avoidant flight behavior from birds released into a corridor containing a physical obstacle. I selected these signals to test multiple frequency levels (4-6 kHz and 6-8 kHz) and temporal modulation patterns (broadband and oscillating) to determine which combination of sound attributes is the most detectable to a bird in flight. I found that sound treatments in general cause birds to maintain a greater distance from potential hazards and to adjust their flight trajectories before coming close to obstacles, with statistically non-significant trends in the data suggesting that the 4-6 kHz oscillating signal does this most effectively. These findings can be used to refine acoustic warning signals and to demonstrate the value in using behavioral data to assess collision risk.

Introduction

North American bird populations have declined by nearly 30% in the last 50 years.[1] Anthropogenic stressors are largely responsible for this trend. Collisions with humanmade structures are among the most significant sources of accidental bird mortality,[2] causing hundreds of millions of bird deaths in the United States annually.[3] Avian biodiversity loss has serious ecological and financial consequences, highlighting the need to reduce bird mortality in order to stabilize ecosystems and appease economic stakeholders.

Birds provide a number of important ecological services, so avian population declines may have tangible ramifications throughout the ecosystems they inhabit. Birds are important for pest reduction in agricultural landscapes,[4,5,6] with insectivorous birds globally consuming around 400 million metric tons of prey biomass each year.[7] This predation results in reduced damage to plants[8] and increased crop yields.[9,10] Therefore, bird declines may result in tangible agricultural consequences with the potential to affect the food supply. Birds are also important for seed dispersal throughout temperate landscapes.[11] Thus, bird declines may alter plant compositions throughout ecosystems, which may have bottom-up effects on other organisms that rely on plants for energy or habitat.

Damages from bird collisions also impose significant financial burdens on a variety of industries. In aviation industries, for example, total costs from delays, cancellations, and damages related to bird collisions are conservatively estimated at around US $1.2 billion each year globally.[12] Furthermore, industries may experience damaged reputations due to associations with bird deaths. Bird collisions can tarnish the image of otherwise environmentally reputable companies like wind energy groups. Some critics use bird mortality as justification to pull support from wind power,[13] creating conflict with clean energy goals. As a result, many stakeholders, from conservationists to urban designers to communications and energy industries, should have a vested interest in reducing the incidence of bird strikes.

While a variety of strategies have been implemented to resolve the collision crisis, bird strikes continue to occur with increasing frequency in urban areas. Human development has fragmented natural landscapes with buildings, communication towers, wind turbines, and other tall objects to which birds are not adapted. Birds tend to look downward and rely predominantly on lateral and binocular vision while in flight,[14] limiting their ability to detect obstacles directly in front of them.[15] As such, visual preventative measures like ultraviolet window films,[16] lights,[17] lasers,[18] and boldly-patterned decals[19] have been met with only limited effectiveness and reveal great interspecific variation in success.[20]

Multimodal warning signals may help resolve the shortcomings of current collision deterrents by engaging with multiple sensory systems at the same time to increase avian attention to the surrounding environment. In particular, sound could be used as a preliminary warning signal to birds as they approach tall objects, raising their awareness so that they can visually detect the threat and change direction before a collision can occur. Acoustic warning signals have been demonstrated to cause birds to slow and redirect their flight paths away from collision hazards.[21] However, more research is necessary to determine which sounds are the most effective to use as auditory deterrents; the relative detectability of various sound qualities to birds may mean that some acoustic warning signals are more effective than others.

Here, I evaluated four sound signals with different frequency ranges and modulation patterns to determine whether sound signals with particular characteristics more effectively elicit collision-avoidance behaviors from birds. Motionless birds are generally most sensitive to frequencies between 1 and 5 kHz.[22] However, birds may experience different sound environments when in flight than when motionless, and no previous studies have addressed this possible discrepancy to determine whether peak auditory sensitivity shifts during flight. A flying bird's sound environment likely reflects a combination of factors such as flapping wings, moving air currents, and Doppler shifts of ambient noise. Similarly, birds may more readily habituate to constant, unchanging tones than to sounds that oscillate in frequency over time, rendering temporally modulated sound signals more effective as deterrents.

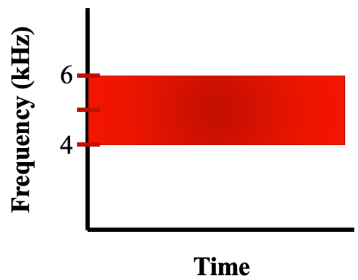
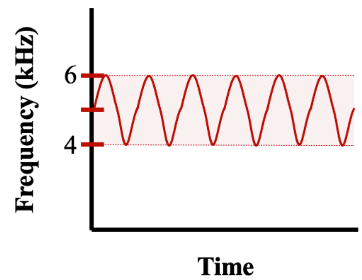
I hypothesized that higher frequency sound signals that oscillate in pitch are the most effective warning signals because they are most easily detectable above the low-frequency background noise birds experience while in flight. As such, I predicted that birds subjected to such signals would reduce their velocity, increase the distance between themselves and flight obstacles, and adjust the trajectory of their flight sooner than birds exposed to other types of sound signals, all of which are behaviors that would contribute to a reduction in the risk of a fatal collision.

Methods

Study System

I performed flight trials using captive zebra finches (*Taeniopygia guttata*) housed in free-flight conditions in an aviary in Williamsburg, Virginia. Zebra finches are native to Australia, but they are an effective study system because their hearing capabilities and behaviors are representative of wild North American songbirds that are vulnerable to collisions locally. I collected repeated measures of flights from 25 individuals, identifiable by unique color band combinations, in order to account for possible individual variation in flight behaviors.

Table 1. Sound treatments. Four sound signals were created from all possible combinations of two frequency levels (4-6 kHz and 6-8 kHz) and two temporal sound patterns ("Band" – a continuous spectrum of sound waves played simultaneously within the respective frequency range – and "Oscillation" – sweeping up and down within the respective frequency range, with only one pitch played at a time). Amplitude is held constant at approximately 85dB.

<table>
<tr><th></th><th colspan="3">Temporal Sound Pattern</th></tr>
<tr><th rowspan="3">Frequency Level</th><th></th><th>Band</th><th>Oscillation</th></tr>
<tr><td>4-6 kHz</td><td>
</td><td>
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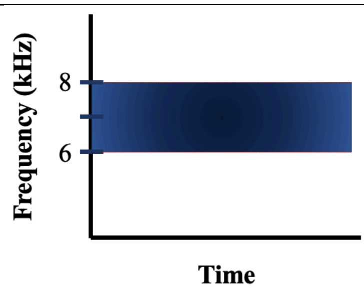
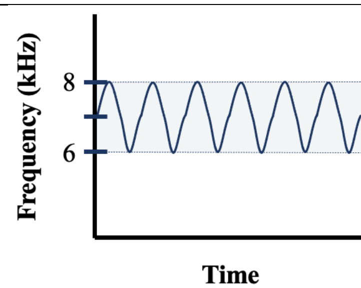
<tr><td>6-8 kHz</td><td>
</td><td>
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Sound Treatments

To test the effectiveness of different acoustic deterrents to birds in flight, I created sound signals from all combinations of two frequency levels and two temporal sound patterns (Table 1) using free professional online software from WavTones[23] and AudioCheck.[24]

Flight Trials

One at a time, I released birds into a dark tunnel leading into an outdoor flight corridor with a Holosonics directional speaker placed in front of an obstacle directly in their flight path (Figure 1). I measured flight behaviors from recordings on three Go-Pro Hero 7 Black video cameras (60fps, 1440 resolution, 4:3 aspect ratio, linear shooting mode). In treatment flights, sound signals played for the entire duration of the bird's flight; in control flights, no sound played from the speaker, but the speaker remained in place. I regarded flights as complete when the bird either changed direction by more than 90 degrees relative to the obstacle or landed somewhere within the outdoor flight corridor.

Each bird was exposed to all four warning signals in a randomized order, and each treatment flight occurred within 24-48 hours of a preceding control flight, for a total of eight flights. Birds had five to seven days to recover under normal housing conditions before their exposure to the next control-treatment pairing. Pairing treatments with repeated control flights established a baseline flight quality for each bird at each time point, allowing me to monitor whether any changes in flight patterns resulted from the different treatments or from a shift in flight behavior after repeated exposure to the corridor setting.

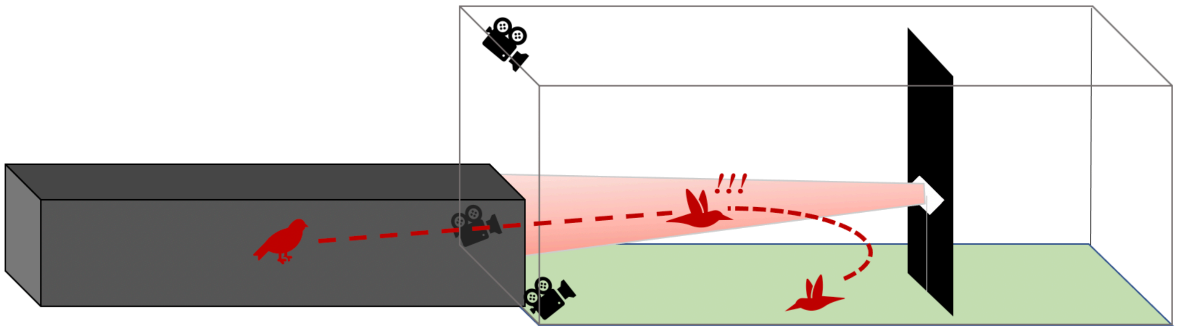

Figure 1: Flight corridor schematic. Birds are released inside a dark tunnel leading into an outdoor corridor. A tarp hanging ceiling-to-floor acts as a potential collision hazard, and a speaker is placed adjacent to the tarp, angled at the dark tunnel. In treatment flights, a narrow beam of directional sound is emitted from the speaker to the end of the dark tunnel. The bird's flight pattern is recorded after its emergence from the dark tunnel using three Go-Pro cameras.

I considered a flight to be successful if the bird appeared within the field of view of at least two of the three cameras – approximately 1m beyond the end of the dark tunnel through the end of the outdoor corridor – which implies that the bird has flown far enough to interact with the obstacle and sound signal, if used. Flights were failures if not visible from at least two camera views within this area, as multiple angles are necessary for flight digitization, and flights that did not proceed far enough to be captured on video were unlikely to contain meaningful interactions.

Birds that failed up to two of the eight flights were given one month of latency before being exposed again to the missing control-treatment pairings and were retained in the study if these make-up flights were successful. Birds that failed more than two flights were dropped from the study; this was necessary for only six individuals out of the original cohort of 25, resulting in a final sample size of 19.

<u>Flight Digitization and Metric Extraction</u>

Using Argus software,[25] I synchronized and calibrated recordings from the three camera angles and manually digitized the bird's position in every frame of its flight duration from all three camera views. The overlapping flight tracks from multiple perspectives generated three-dimensional coordinates of the bird's position through space and time via direct linear transformation,[26] where all coordinates are given relative to the origin at the center of the speaker (Figure 2). After obtaining coordinates for every bird in each of its eight flights, I computed a variety of metrics (Table 2), including the bird's overall velocity, minimum distance from both the obstacle and the speaker, and changes in flight trajectory.

I inferred relative collision risk from these metrics. Flights in which birds move at a lower velocity, maintain a greater distance from obstacles, and/or adjust their trajectory far away from hazards are most likely to successfully avoid a fatal collision. Furthermore, assessing distance from the speaker and from the obstacle separately allows insight into whether avoidant behaviors are in response to the warning signal or visual detection of the flight hazard.

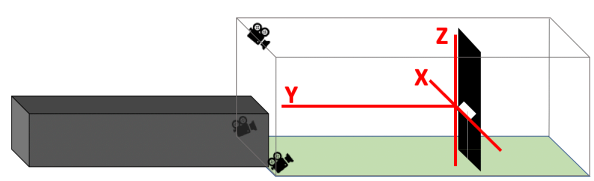

Figure 2. Positions of *X*-, *Y*-, and *Z*-axes within flight corridor. The *X*-axis spans from side to side, the *Y*-axis spans down the length of the corridor, and the *Z*-axis spans floor to ceiling. The three axes intersect at the center of the speaker to form the origin.

Table 2. Flight metrics. Seven metrics of collision avoidance were computed from birds' three-dimensional coordinates, related to flight velocity, distance from speaker and collision hazard, and change in flight trajectory. Distance metrics are calculated with respect to both the speaker and the obstacle to separately consider whether any observed avoidance is in response to auditory detection of the warning signal or visual detection of the obstacle.

Metric Description	Calculation
Within-flight change in velocity	Average velocity in final third of flight minus average velocity in first third of flight
Average velocity	Average velocity over the entire course of the flight
Minimum distance from obstacle	Smallest vector distance between bird's coordinates and the obstacle at $X = 0$ and $Y = 0$ (excluding the Z plane, as the obstacle occupies all possible Z-coordinates)
Minimum distance from speaker	Smallest vector distance between bird's coordinates and the speaker at $X = 0$, $Y = 0$, and $Z = 0$ (including the Z plane to account for bird's vertical position relative to the sound beam)
Proportion of flight completed when bird makes greatest adjustment in flight angle	Frame at which greatest angular adjustment occurs divided by total number of frames in a flight
Distance from obstacle when bird makes greatest adjustment in flight angle	Vector distance from obstacle (excluding Z plane) in the frame of overall flight during which bird makes greatest angular adjustment
Distance from speaker when bird makes greatest adjustment in flight angle	Vector distance from speaker (including Z plane) in the frame of overall flight during which bird makes greatest angular adjustment

Statistical Analyses

Treatments vs. Control

To determine whether birds exhibited different flight behaviors when exposed to sound treatments than in control flights, I ran three-factor repeated measures analyses of variance (ANOVA) with interaction effects. Factors included were the control vs. treatment flights for each bird, different frequency levels, and temporal modulation patterns of sound signals, as well as all possible interactions between these attributes. Bird identity was given as a unique value to signify repeated measures.

Comparisons of Sound Signals

To make comparisons between the different sound signals, I subtracted the metric calculations of each control flight from their paired treatment flights to provide each treatment measurement in terms of the difference from its baseline. For example, a positive distance value would indicate that the bird maintained a greater distance in a treatment flight than in the matching control, and a negative average velocity value would indicate that the bird flew more slowly in the treatment than in the control. This standardizes the differences in flight behavior recorded at each time point to allow for within-individual comparisons between treatments.

I compared the relative differences in each of the seven flight responses across each of the four sound signals using two-way repeated measures ANOVAs with interaction effects. Here, factors included were the frequency level, temporal modulation pattern, and the interaction between these two sound attributes, with bird identity considered for repeated measures. I also conducted a principal components analysis (PCA) including all seven flight metrics as possible loadings, and I analyzed differences in PC1 and PC2 scores separately in response to the four sound signals through two-way repeated measures ANOVAs. All statistical analyses were performed using R version 3.6.3.

Results

Treatments vs. Control

Birds maintained a greater minimum distance from both the obstacle ($p = 0.0002$) and the speaker ($p < 0.0001$) when sound treatments were used than in control flights. Birds also made the greatest adjustment in their flight angles at a further distance away from both the obstacle ($p < 0.0001$) and the speaker ($p = 0.0002$) when treatments were used. Within-flight change in velocity, average velocity, and the proportion of flight completed during the greatest angular adjustment did not differ between control and treatment flights (all $p > 0.05$).

Comparisons of Sound Signals

For each of the seven metrics, I found no differences in flight behavior between the four sound signals, with all $p > 0.05$ in response to frequency level, temporal modulation pattern, and the interaction effect. Despite the lack of statistical significance, I observed patterns of avoidant behaviors in response to the 4-6 kHz oscillation and to the 6-8 kHz band. For example, birds tended to maintain the greatest average minimum distance between themselves and the obstacle when exposed to these two signals as compared to the 4-6 kHz band or the 6-8 kHz oscillation (Figure 3). I observed a nearly identical pattern for the minimum distance measured between birds and the speaker. The lowest overall average flight velocity was also recorded from these two signals. With the 4-6 kHz oscillating signal in particular, birds made their greatest adjustment of flight angle earlier and at a greater distance from both the obstacle and the speaker. Figures for these other metrics are omitted here for brevity but can be provided upon request.

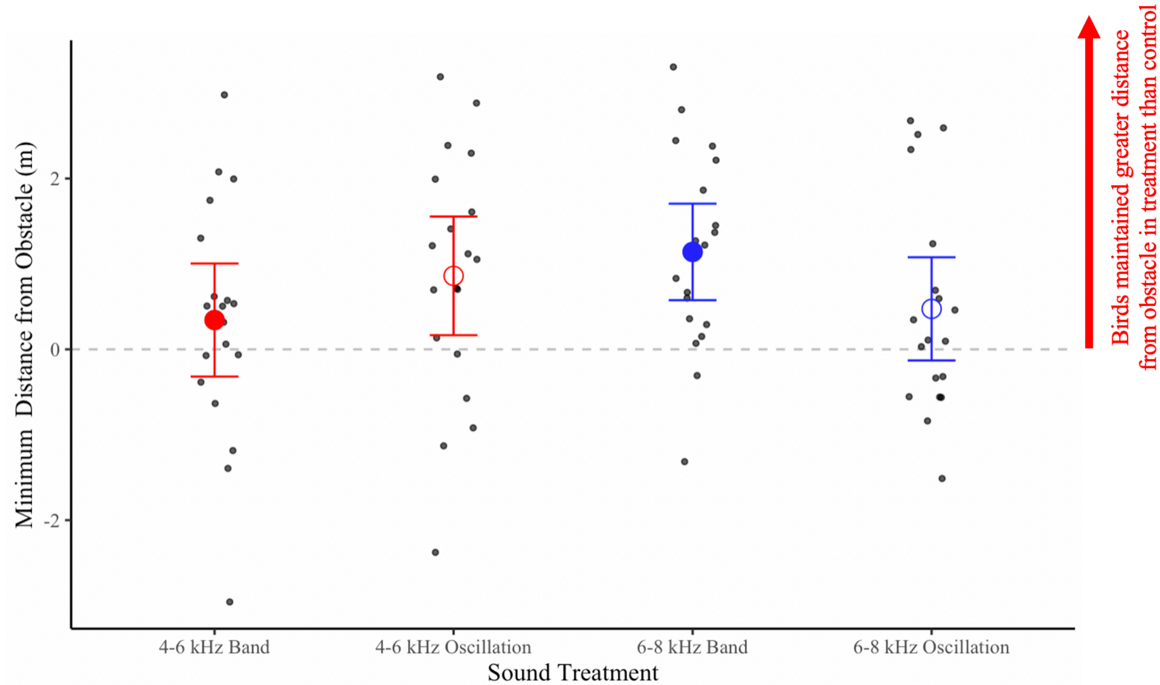

Figure 3: Birds maintain a greater minimum distance from potential flight hazards when exposed to 4-6 kHz oscillating signal and 6-8 kHz band. Shown is the average minimum distance ± 95% CI between birds and the obstacle (m) for each of four sound signals (4-6 kHz in red, 6-8 kHz in blue; band signals given in closed circles, oscillating signals given in open circles). Measurements are scaled based on each bird's baseline performance by subtracting each control measurement from its respective treatment. Red arrow indicates the hypothesized directionality of collision-avoidant behaviors with respect to the control, where the dotted line at a distance of 0 indicates that there was no difference in the minimum distance from the obstacle between treatment and control flights.

PCA loadings are shown in Table 3, wherein components 1 and 2 are together responsible for 81% of the observed variance. Based on the directionality of these loadings, component 1 ("PC1") is positively associated with flights in which the bird flew more quickly, came closer to the obstacle and the speaker, and adjusted its angle with a lower distance from the obstacle and the speaker in the treatment than in the control. Therefore, a *negative* score for PC1 would indicate collision avoidance in the form of flying more slowly and further away from the collision threat. Component 2 ("PC2") is positively associated with flights in which the bird flew more quickly and adjusted its angle earlier and further from the obstacle and speaker in the treatment than in the control. Therefore, a positive score for PC2 would indicate collision avoidance in the form of adjusting the flight trajectory before coming close to the collision threat.

PC1 and PC2 scores did not differ significantly in response to different frequency levels, temporal modulation patterns, or the interaction effect (all $p > 0.05$). However, I observed an additional non-statistically-supported trend indicating that birds exposed to the 4-6 kHz oscillating signal had the lowest average scores for PC1 and the highest average scores for PC2 (Figure 4), thus maximizing both types of collision-avoidant behaviors. Birds also had lower scores for both PC1 and PC2 in response to the 6-8 kHz band than to the remaining two signals, indicating that any avoidant behaviors in response to this signal more likely occurred through a reduction in velocity and a greater distance maintained from the hazards than from an early adjustment in angle. The 4-6 kHz band and 6-8 kHz oscillation did not tend to invoke any of these collision avoidance behaviors as both had slightly positive PC1 scores and PC2 scores of approximately 0.

Table 3. Flight metric loadings in principal components 1 and 2. Positive loadings are shown in green and negative loadings are shown in red.

Metric Description	PC 1 Loading	PC 2 Loading
Within-flight change in velocity	0.167	0.684
Average velocity	0.398	0.515
Minimum distance from obstacle	-0.473	-
Minimum distance from speaker	-0.423	-
Proportion of flight completed when bird makes greatest adjustment in flight angle	-	-0.106
Distance from obstacle when bird makes greatest adjustment in flight angle	-0.463	0.342
Distance from speaker when bird makes greatest adjustment in flight angle	-0.440	0.370

Discussion

I found that sound treatments cause birds to maintain a greater distance from potential flight hazards and to adjust their flight trajectories before coming close to these hazards. In addition, I observed consistent non-statistically-supported trends indicating that birds exhibited the most collision-avoidant behaviors in response to the 4-6 kHz oscillating signal in comparison to all others tested here.

If these trends reflect deeper biological meaning, these results do not support the hypothesis proposed here that higher frequency signals are more detectable to birds above background noise. However, they do align well with our existing knowledge of the frequency range at which avian auditory sensitivity is maximized. Perhaps the sound environment surrounding this flight corridor experimental setup does not provide a sufficient level of lower-frequency background noise to mask the 4-6 kHz signal, and the sound generated by the

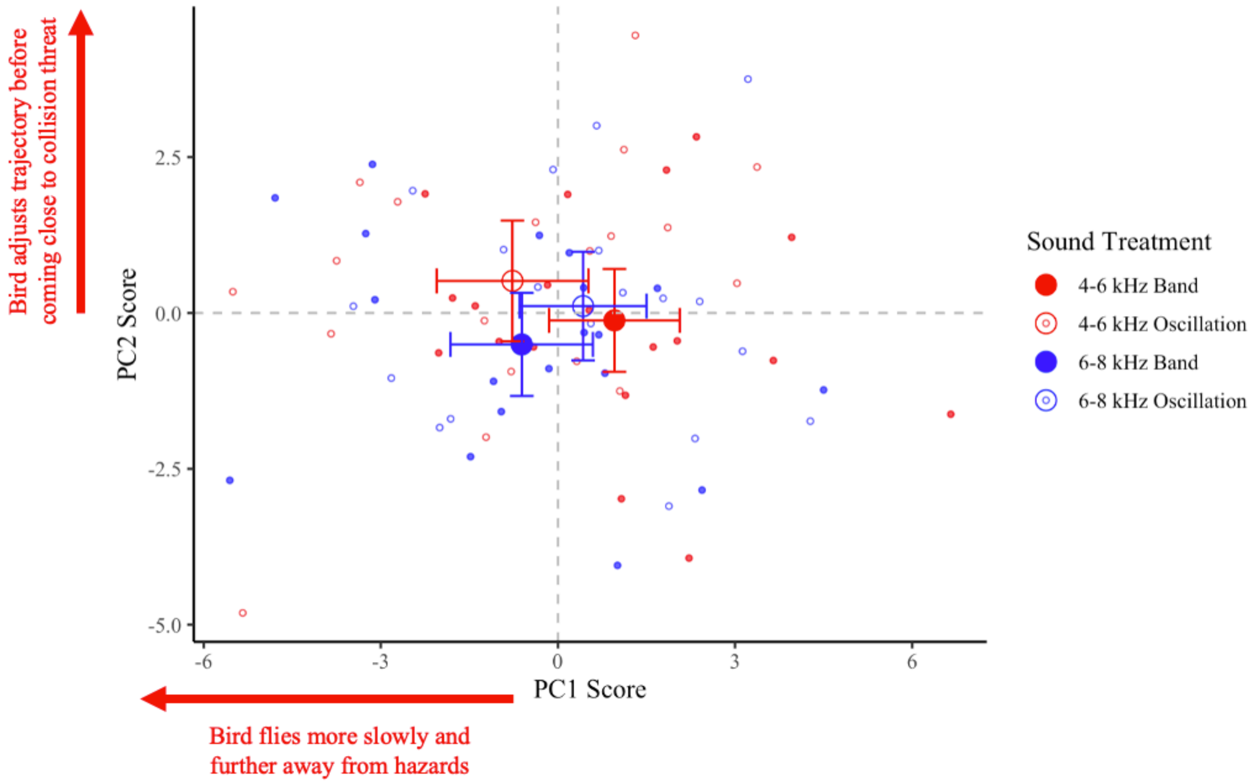

Figure 4: Birds exhibit two suites of collision-avoidant behaviors in response to 4-6 kHz oscillating signal. A PCA was performed using the seven flight metrics, with the resulting loadings described in Table 3. Shown is the average score for PC1 and PC2 ± 95% CI for each of four sound signals (4-6 kHz in red, 6-8 kHz in blue; band signals given in closed circles, oscillating signals given in open circles), scaled by each bird's performance in its control flight. Red arrows indicate the hypothesized directionality of collision-avoidant behaviors, where dotted lines at PC scores of 0 indicate that there is no difference in avoidant behaviors between treatment and control. Thus, flights falling in the upper-left quadrant have maximized both suites of avoidant behaviors.

motion of flight alone may not be loud enough or in the correct frequency range to drown out these signals. Future iterations of this research could attempt to simulate the noise environment of a landscape in which birds experience collision risks (such as a wind farm) to determine whether these results are consistent when there is more background noise that may affect the relative detectability of each of these signals.

The fact that birds maintained a greater distance from *both* the speaker *and* the obstacle during treatment flights suggests a deterrence that was stimulated via both acoustic and visual cues. In addition, birds made their greatest angle adjustment at a further distance from the speaker and the obstacle in the presence of sound signals. This early diversion in their flight trajectory suggests that the birds became aware of the obstacle in the tunnel earlier when warning signals were used, allowing them time to adjust their angle away from the object in their path. This finding may also explain why the average flight velocity did not differ between birds in treatments and controls, as it may not have been necessary to slow down in avoidance of a collision when birds are aware of a hazard and keeping a safe distance.

The effectiveness of these signals in a controlled setting may suggest similar success in practical use. My finding that sound treatments in general elicit collision avoidance behaviors (with only statistically insignificant differences between different signals) provides encouraging evidence that implementing any type of acoustic warning signal may increase birds' attention to their surrounding environments, reducing the risk of a fatal collision.

Importantly, this research underscores the value in using behavioral data to supplement our understanding of avian collision risk and to evaluate collision mitigation strategies. As seen here, birds employ locomotive responses similar to anti-predator behaviors[27] in order to evade collisions. It is essential to tailor anti-collision technology to birds' sensory ecology in order to maximize the effectiveness of these stimuli. Additionally, most current metrics of collision risk are derived by collecting carcasses from hazardous landscapes, which may substantially undercount mortality from collisions due to the effects of scavenger removal.[28,29] Furthermore, not all collisions are fatal, and some birds may endure physical damage in the aftermath of strikes that is debilitating to their livelihood despite being sublethal. Considering adjustments in flight behavior as proxy evidence for the relative risk of a fatal or injury-inducing collision could allow us to better interpret some of these nuanced assessments of the threats posed to birds by manmade obstacles and of the innovations intended to reduce this risk.

This study reinforces a growing body of evidence that acoustic warning signals can be used to potentially reduce bird mortality and injury from collisions. In addition to curbing avian population decline and preserving birds' valuable roles within ecosystems, this has positive implications for groups that experience conflict due to bird strikes (such as the aviation, power, and communications industries). Utilizing acoustic warning signals should reduce the damage to humanmade structures caused by bird collisions in addition to reducing the collisions themselves, which is economically desirable and potentially even lifesaving when considering the hazards that bird strikes create for aircrafts.[30,31] Such technology may also permit the expansion of renewable wind energy with lessened disturbance to adjacent avifauna.

Human development has been a major source of conflict with wildlife. However, the same innovation that drives urbanization and development can also be used to devise solutions for the associated threats to wildlife. Collision-reduction technology can allow us to share a commensal relationship rather than conflict with avian fauna. Continuing to develop, refine, and implement acoustic warning signals designed to reduce avian collision risk will minimize the need to impose unrealistic constraints on our own development while also reducing the consequences of this development on wildlife.

Acknowledgments

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