Does Sound Help Prevent Birds from Flying into Objects?

Nicole Marie Ingrassia

Howell, NJ USA

Zoology B.S., Oregon State University, 2012

A Thesis presented to the Graduate Faculty

of the College of William and Mary in Candidacy for the Degree of

Master of Science

Biology Department

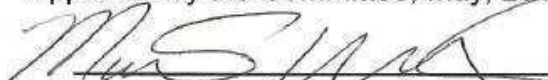The College of William and Mary

August 2016

APPROVAL PAGE

This Thesis is submitted in partial fulfillment of
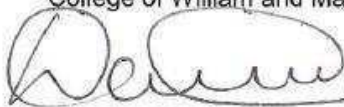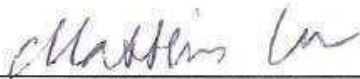the requirements for the degree of

Master of Science

_____
Nicole Ingrassia

Approved by the Committee, May, 2016

_____   Matthew Wawersih
Committee Chair   (for J. Swaddle)
Professor John Swaddle, Biology
College of William and Mary

_____
Professor Dan Cristol, Biology
College of William and Mary

_____
Associate Professor Matthias Leu, Biology
College of William and Mary

COMPLIANCE PAGE

Research approved by

<u>Institutional Animal Care and Use Committee</u>

Protocol number(s): IACUC 2015-11-16-10733-jpswad

Date(s) of approval: November 16, 2015

ABSTRACT

Bird strike is the often fatal collision between a bird and a surface, such as a window or tower. Collisions kill millions of birds each year in the US alone, and cost industries millions of dollars per year. As more buildings, wind turbines, communication towers and other structures are built, bird strikes and its associated costs are predicted to increase. Researchers have explored mitigative measures to alleviate bird strikes but to date none have solved this growing problem. Recent research suggests that current technologies fail because their design does not take into account birds' sensory ecology, including habituation to loud sounds and some species may lack the ability to effectively see visual deterrents while flying. In this study we explored an acoustic mitigative measure against bird strike. Our goal was to use directional sound as an instrument to warn flying birds of an upcoming visible barrier in their flight path. We hypothesized that when birds experienced a strong sound field (80 dB SPL) in the presence of a visible mist net, they would increase their body and tail angles of attack, enabling them to slow down. Our results show that when flying zebra finches (*Taeniopygia guttata*) encountered a loud sound field in front of a visible barrier, they slowed their flight (relative to a control flight) by approximately 25% and simultaneously increased their body and tail angles of attack by 25° and 50°, respectively. This alteration of velocity and flight posture will likely increase birds' capacity to maneuver, due to increased tail drag and improved tail lift, and potentially afford individuals more time to initiate avoidance maneuvers. Collectively, our results support the conclusion that a conspicuous sound can decrease birds' risk of striking a static surface or object. Our study suggests that emitting sound in front of windows, wind turbines, power lines, as well as cell, radio and communication towers could decrease bird strikes and associated damage and costs.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

Bird strike is the often fatal collision between a bird and a surface, such as a building, window, communication tower, or wind turbine (Klem 1990, Veltri and Klem 2005). While exact numbers are unknown (Loss et al 2012), recent research indicates that approximately 6.8 million birds per year die in North America as a result of collisions with communication towers (Longcore et al. 2012), and approximately 365 to 988 million birds die every year as a result of flying into buildings in the US (Loss et al. 2014). Bird strike appears to be the largest source of accidental bird mortalities worldwide (Klem 2004) and is likely to be underreported due to challenges with reporting bird fatalities in a standardized fashion (Erickson et al. 2005) and because many collision sites are never visited to find dead birds (Erickson et al. 2005, Longcore et al. 2008, Shaw et al. 2010). Communications towers approved by the FCC are not required to monitor or record bird fatalities (Longcore et al. 2008), so birds dying at communication towers are largely not represented except during researcher-initiated studies. Challenges to reporting fatalities accurately include issues with search efficiency (Smallwood 2008), disappearance of carcasses (Hötker et al. 2008), and methods of reporting fatalities that are not adjusted in accordance to the situation and species studied (Drewitt and Langston 2008).

Despite the likelihood of underreporting collision fatalities, it is established that bird strike has increased steadily and is expected to continue to increase in both the US and in developing countries (Drewitt and Langston 2008, Paula et al. 2011). Due to increasing human populations and bandwidth usage, the structures birds fly into are all increasing in abundance (Bevanger 1994, Ogden 1996, Kerlinger 2000, Manville II 1999, Erickson et al. 2005, ABS Energy

1

Research 2006, Patterson 2012, Drewitt and Langston 2008, Wind Vision Report 2012). For example, wind power generation has tripled between 2008 and 2013, with goals to produce 20% of the energy use in the U.S. by 2020 (Wind Vision Report 2012). The increase of structures birds fly into means we can anticipate an increase in bird strike as well.

Despite the reports of large numbers of bird deaths due to bird strike, it is debated as to whether or not bird strike causes long-term population declines (Arnold and Zink 2011, Schaub et al. 2011, Klem 2012, Longcore et al. 2013). However, even if bird strike does not make a permanent dent in population sizes of very abundant avian species, it is likely to affect populations of species of conservation concern in some but not all regions (Bevanger 1994, Bevanger 1998, Manville II 2005, Longcore et al. 2013, Loss et al 2014). For example, it is well-established that wind turbines pose a risk to birds of prey and may contribute to population declines of vulnerable species such as Griffon Vultures, *Gyps fulvus* (Lekuona and Ursúa 2007) and Golden Eagles, *Aquila chrysaetos* (Hunt 2002, Hunt and Hunt 2006). Several threatened species of bustards are particularly susceptible to collision with power lines (Silva et al. 2014): the endangered Ludwig's Bustard, *Neotis ludwigii* (Jenkins et al. 2011), threatened Houbara Bustard, *Chlamydotis undulata*, (Garcia-del-Rey et al. 2011) and near-threatened Denham's Bustard, *Neotis denhami* (Shaw 2009). In combination with other anthropocentric threats these species face (such as habitat loss and hunting), bird strike is a significant part of their population declines, and for some endangered species collision is the most important mortality source (Manville 2009). Mitigation of collisions, therefore, has the potential to help conserve biodiversity.

Not only does bird strike cause major mortality events, it also causes significant financial costs for multiple industries (e.g. wind energy, construction, communications, and power industries). For example, bird strike costs approximately $500 million per year in the US alone (Dale 2009). Bird strike also impacts permitting and construction in relative industries, which is a financial burden, causes delays, and can result in a loss of potential sites. For instance, in order to obtain permits for wind turbines, the wind power industry must comply with The Endangered Species Act, Migratory Bird Treaty Act, and The Bald and Golden Eagle Protection Act. In doing so, the industry must invest money and other resources into replacing eagles killed by collision, for example, and must adhere to avoidance and minimization measures before siting, construction, or operation of wind energy production where eagles are present. The wind industry also invests in research into population impacts caused by wind turbines on other species, such as Prairie Chicken, *Tympanuchus cupido*, Sage Grouse, *Centrocercus urophasianus*, and Whooping Cranes, *Grus americana* (Wind Energy Vision report 2012).

In attempt to drive down both the costs of bird strike and the number of birds dying, researchers have explored many mitigative measures against bird strike. One such mitigative measure is an acoustic deterrent. Acoustic deterrents attempt to exploit birds' sensitivity to noise. Birds generally hear well within a smaller frequency range than humans and have ears that are structurally different but operate similarly to mammals (Dooling 1980). They can therefore react to loud noises, such as pyrotechnics or even firing ammunition in the areas surrounding structures (Montoney and Boggs 1993), or respond to artificial alarm calls or other biologically-inspired noises (Jasoslow 1979, Berge et al. 2007, Drewitt and Langston 2008). However, habituation can occur when a bird becomes accustomed to a noise and no longer

3

responds to it. In some cases, habituation has occurred in response to pyrotechnics (Blokpoel 1976, Inglis 1980, Slater 1980, Summers 1985), and remains a problem when using acoustic deterrents overall (Dooling 2002).

Another common mitigative measure is the use of visual deterrents. This means using some kind of marking on an object to make it more visible to birds, in hopes of deterring them from flying into it (Drewitt and Langston 2008, Klem 1989, Klem 2004). For example, hanging parachute cords on windows can make them more visible to birds (Klem and Saenger 2013). Some visual deterrents, such as placing decoys or using interior patterns or curtains at windows, have been tested and found to be ineffective at preventing collision, (Klem 1990, Ogden 1996). However, recent research has narrowed down effective window markings for some species (Rössler et al. 2015) and effective markings continue to be explored. Marking wires at power lines decreases collision and is recommended as the best way to reduce collision with power lines (Barrientos et al. 2011, Alonso and Alonso 1994). The main problem in using markers alone is that they do not prevent certain species from flying into power lines (Silva et al. 2014). This is because species with limited binocular vision (e.g. 60° vertical extent of forward-facing vision in a bustard versus 120° in a white stork, *Ciconia ciconia*) may not see markers (or power lines) as they fly (Martin 2011). Therefore, while some types of visual deterrents (e.g. some window and wire markers) against bird strike are successful, more needs to be done to mitigate bird strike of species that do not respond well to visual markers alone.

Despite common mitigative measures against bird strike, mortal collisions are still on the rise. There is a call for development of new tools to prevent bird strike (Drewitt and

Langston 2008, Martin and Shaw 2010, Martin 2011, Marques et al. 2014). It is not surprising that birds continue to fly into visible objects, because birds do not perceive the world around them in the same way that people do (Martin 2010). Something that is clearly visible to people may not be as readily apparent to a flying bird. For example, bustards and cranes regularly fly into marked and unmarked power lines. Studies show that a large factor in this behavior is due to their extremely limited binocular vision (Martin and Shaw 2010, Martin 2011). Research suggests that a more successful wildlife management strategy should employ a sensory-ecology approach (Madliger 2012). This means that incorporating biological factors about birds, such as their vision while flying, into mitigative strategies is likely to result in more successful outcomes (Martin 2011, Madliger 2012).

In helping to elucidate why birds fly into visible objects, research on their sensory ecology has produced powerful insight into how birds see the world in front of them. Forward-facing, or binocular, vision in birds is extremely limited compared to humans. Birds have laterally-placed eyes, on the sides of their head. Due to the location of birds' eyes, the optical system in each eye is not parallel. This means that monocular vision, not binocular vision, contains the area of highest resolution. In fact, for some species, moving their central vision by rotating their eyes backward can completely abolish their binocular vision. For example, if a Cattle Egret, *Bubulcus ibis*, rolls both its eyes backwards, it will experience a 14-degree gap in any forward vision, but will gain 27-degrees of visual coverage to the rear of its head (Martin 2007). When looking behind them while in flight, then, Cattle Egrets and other species similar to them cannot respond to markers or other visual deterrents against collision. These birds and

similar species such as cranes and bustards -- sometimes simply cannot see visual deterrents or the objects they fly into.

Even in species that do not experience a total blind spot looking ahead, their narrow binocular range of view of 20-30 degrees on average, and the fact that their binocular vision is actually their peripheral vision (Martin 2007), still presents problems to relying on visual markers alone to deter bird strike. Research suggests that birds are less likely to fly into things they can both see and hear (Dooling 2002). Proposed solutions to reduce bird strike include using a device to draw a bird's attention to a visible object (Martin 2011). Such a device could be a "warning sound" to distract birds from the flight path they are on toward the object (Martin 2011). This sound could prime their attention to the presence of the visible yet hazardous object in front of them-- something they may not otherwise see.

In this study, we examined using sound as an instrument to warn flying birds of a visible barrier in their flight path. Our goal was to see if sound can potentially prevent birds from flying into visible objects. We termed our sound source an "Acoustic Lighthouse" because it serves as a sonic beacon to warn birds the way a lighthouse warns ships of rocks. Prior to experimental trials, we trained birds to fly down a flight corridor and through an empty wooden frame to ensure they would fly from start to finish through our test area. Once birds were trained, we proceeded to experimental trials. During experimental trials, each bird received, in random order, each of three treatments: a mist net by itself in the frame, sound only from the speaker with no mist net, or, a mist net in the frame and sound from the speaker. Using high speed video capture, we examined if the Acoustic Lighthouse, a loud sound field (80+ dB SPL)

placed in front of a static visible object alerted flying zebra finches (*Taeniopygia guttata*) to the presence of the object and alters flight behavior in ways that mitigate or potentially avoid collision. Within an experimental context, we tested whether the Acoustic Lighthouse caused flying birds to alter their velocity as they approached the strike surface (in our study, a harmless mist net). We also explored whether this sound field caused the flying birds to change the angle of attack of their bodies and tails before the mist net. We predicted that experiencing a loud sound field just prior to a visible strike surface would cause the birds to slow down and increase their angle of attack, resulting in a more vertical flight posture, which is indicative of a bird attempting evasive maneuvers.

Methods

Subjects and Housing

To test our hypotheses we used a flock of 8 male and 10 female adult zebra finches. The birds were housed indoors in an approximately 3 x 3.3m free-flight room on a 14:10 L:D photoperiod with ad libitum access to food (millet seed, Avian Science Super Finch by Volkman), grit, and drinking and bathing water. The room contained two open-sided boxes, approximately 0.42m long by 0.25m deep by 0.25m tall. These boxes resembled the boxes we used during experimentation. These training boxes sat 0.91m from the ground, and had wooden dowels fixed to each end for the birds to perch on. There were no other perches in the room. We framed the training boxes with orange flagging tape to make them conspicuous, and we placed them at opposite corners of the room in order to encourage flight between the boxes. The

birds' food and grit was placed inside the boxes, hence birds needed to visit these boxes many times a day. Behind one box, visible to the birds, was one small cage (0.25m x 0.20m x 0.40m). This cage was a replicate of the cage at the end of the flight corridor (Figure 1). In this way the birds became familiar with objects of importance in the flight corridor test chamber.

We housed three additional adult zebra finches (1 male and 2 females) in a metal cage (0.59 x 0.41 x 0.41m) placed in a separate room under the same photoperiod as the other birds and with ad libitum access to the same food, grit, and water. These birds, known as "stimulus" birds, were used in the end cage (Figure 1) during training and trials.

Flight Corridor

Our experimental arena was an outdoor flight corridor with an approximate size of 8.22m length x 2.44m width x 2.13m height, Figure 1). The corridor walls were constructed of wire mesh, except for one section (3.12m long) in the middle of one side that was constructed of wooden siding and a 0.91m-wide metal door. The whole corridor had a corrugated plastic roof above the mesh. We lined several walls with thin plastic sheeting to control lighting and to insulate the corridor when flights were performed during colder weather. In the colder months, we used three small, portable electric ceramic heaters for heating. We placed training boxes framed with orange flagging tape, identical to those placed in the housing room, on pedestals 0.91m tall at opposite ends of the corridor. We used one of these boxes, the "start" box, as a release site for all flight trials. We attached a small cardboard tube (0.08m diameter) to the start box. The tube allowed us to place each bird inside of it in the same position, standardizing

the release of birds.   The box at the opposite end was the "end" box. Behind the end box, there was a small (0.25m x 0.40m) cage for the stimulus birds (see Figure 1).

To hold the mist net, we installed a wooden frame, facing the short axis of the corridor 5.58m from the start box. The 0.91m x 2.13m wooden frame reached from floor to ceiling of the corridor and could be either empty or contain the mist net. There were gaps of approximately 0.77m on either side, between the frame and the respective wall of the corridor Figure 1). In order to help contain the sound generated by the directional speaker and preserve the integrity of the sound column, we lined the ceiling and one wall with convoluted acoustic foam panels (Sound Proof Cow, item # 997161) for 0.8m in front (i.e., toward the "start" box) of the frame (see Figure 1, grey bar). The speaker, Holosonics Audio Spotlight 168i, that produced this sound field (in relevant trials, see below) sat on the center of the floor 0.48m in front of the frame and oriented directly upward, facing the corridor ceiling. In order to help gauge relative distances, we also marked the floor, ceiling, and back wall of the flight corridor with high contrast lines that demarked distances of 1m and 2m from the wooden frame, in the direction of the "start" box.

To record the birds perpendicular to their direction of flight, we used a GoPro Hero4 video camera (camera A on figure 1), on a tripod. We used an identical video camera (camera B on figure 1) on a small tripod on the ground, facing up, to record the birds from underneath. We recorded the trials for five birds with camera B in that position. In order to improve the image by recording from above rather than below, we fixed camera B to the ceiling, via a small tripod, and recorded the rest of the trials with camera B on the ceiling. We carefully aligned

both cameras (A and B) so they could be combined to estimate three-dimensional movements of the birds in flight.

Phase 1: Flight Training

From April to August 2015 (summer training) and from December 2015 to February 2016 (winter training) our birds underwent training in the experimental flight corridor with one experimenter. Each of the birds used in this study received an average of 1,250 minutes (SE = 160) of total training during one or both of these periods. We gave the birds two types of flight training: bidirectional and unidirectional flight training. The majority of training that birds underwent was bidirectional, or two-way, training. The goal of bidirectional training was to encourage birds to fly directly down the middle of the corridor and through the center of the empty wooden frame. In order to achieve this goal, we released a bird from the start box and encouraged the bird, with a loud whistle stimulus, to fly directly down to the end box (Figure 2). Three stimulus birds resided in the small cage at the end box at all times and served as social motivation to fly toward the end box. To encourage social learning, we paired training subjects with a "tutor bird" who did the task readily. We further encouraged birds to fly directly from one box to another (i.e. down the length of the flight corridor without stopping) by blowing a whistle.   If a bird tried to stop, settle, or otherwise turn around while in flight, we waved a net at the bird and whistled, directing it toward its respective destination box.

During these bidirectional training sessions, we recorded whether each bird flew through the center of it while in flight. When an individual bird consistently showed, (e.g. in at least 65% of its overall bidirectional training sessions), that it flew through the wooden frame

on at least half of its flights within any bidirectional training session, then that bird progressed to the next stage of flight training, unidirectional flight training. On average, birds used in this study experienced 8.9 (SE = 1.07) bidirectional training sessions. Each session's duration was, on average, 122 minutes (SE = 6). The number of flights a bird made during a bidirectional training session was on average 12.8 (SE = 1).

We performed unidirectional flight training on single birds without a tutor. The goals of this training were to desensitize the bird to being repeatedly caught between flights, to ensure the bird would release from the start roll repeatedly (Figure 1), and to check and make sure the bird had properly learned to fly from the start to the end box without a tutor. Flights during unidirectional training were initiated in the same manner as bidirectional training flights, however, birds were allowed to fly only from the start to the end box (Figure 1). Then we immediately re-caught a bird in a hand-net after each single flight down the corridor, and released it again for the next training flight. We recorded whether or not each bird flew through the wooden frame during these trials. Birds used in this study experienced one unidirectional training session, containing an average of 3.7 one-way flights (SE = 0.3). Once a bird flew through the center of the empty wooden frame on at least 75% of their unidirectional flights, it was considered to have passed unidirectional flight training. Once a bird passed both bidirectional and unidirectional flight training, it was considered ready to commence experimental flight trials.

Phase 2: Experimental Flight Trials

    Phase 2 was the testing period during which data collection took place. To start the

testing period, also known as a "session", each bird experienced several unidirectional flight

trials. First, a test bird flew through the center of the wooden frame in three consecutive

flights, out of six possible flights. This was known as a "performance check" and its purpose,

similar to previous unidirectional flight training, was to ensure the bird was consistently flying

from the start to the end box through the frame. Once a bird passed its performance check, it

then flew a further 1 to 4 (randomly determined) times, known as control trials. After the

control trial(s), a test bird immediately experienced an experimental treatment. This

sequencing procedure helped contribute to the unpredictability of the occurrence of an

experimental trial, e.g. the experimental trial could happen after as little as one additional flight

after the performance check, or after as much as four additional flights after the performance

check. Immediately after an experimental trial, each bird performed further unidirectional

training flights until it flew through the wooden frame in three consecutive flights or until the

bird had flown six times, whichever occurred first. We ran all trials sequentially without

interruption.

    A bird experienced one experimental treatment per session. The three treatments were

as follows: (i) A taut mist net was inside the wooden frame, *MistNet*, (ii) the speaker in front of

the empty wooden frame played a 2-10 kHz sound at approximately 80 db SPL at 1m above the

speaker, *Sound*, and (iii) both the speaker was turned on to produce the sound field and the

mist net was in the frame, *Both*. There was one day of rest between sessions.

Flight Video Analysis

We video recorded all flight trials in Phase 2 at 120 frames per second, and also recorded an image of a calibration grid at the beginning of any recording session. The calibration grid was a large white board marked with 0.1m x 0.1m squares held perpendicular to the plane of view for each camera and in the center of the flight corridor, where birds were most likely to fly. We extracted videos using GoPro Studio software and exported as .AVI files. We analyzed flight videos for all experimental trials and for the control trial immediately before each experimental trial.

For each relevant video, we extracted single frames using Virtual Dub (Lee 2013) software as high-resolution JPG files. We started frame extraction when the bird first reached the line on the aviary that was 2m in front of the mist net area (Fig. 1), and extracted the proceeding 30 frames. This time period allowed every bird to pass the speaker and potentially make contact with the mist net or pass through the frame. We imported these frames into ImageJ (Rasband 2006). The calibration grid for each day supplied the known distance. In ImageJ, we calibrated each day's frames to the known distances on each camera. Then we were able to generate coordinates in horizontal (x) and vertical (y) planes from the camera that recorded from the side (camera A on figure 1) and from lateral (z) plane from the camera that recorded from the ceiling (or the floor) (camera B on figure 1). The two cameras were synchronized at the 2-m line (start of yellow box in Figure 1). For each bird's side-on video (camera A) we digitized the following points on the body to generate *x* and *y*-direction coordinates: the distal tip of the bill (*bill*), the middle point of a line that bisected the body in a

13

downward direction immediately behind the wing (*body*), and the distal tip of the center of the

tail (*tail*) (see figure 3 for more details). For each ceiling/floor (z) video (camera B) we digitized

the distal tip of the bill only (*bill*) to generate a *z*-direction coordinate. These coordinates

allowed us to measure velocity and angles of attack. An angle of attack is simply the angle

between the front of a flying object, usually a nose on an airplane or the point of the beak on a

bird, and another part of its body. We measured the body and tail angles of attack in order to

obtain useful information about a bird's body position as it flew in our treatments.

From the three-dimensional (*x*, *y*, *z*) coordinates of the *bill* we generated a metric of

velocity for every sequential frame of every flight. We averaged velocity measurements for

every group of 5 frames (i.e. t1 = frames 1 to 5, t2 = frames 6 to 10, t3 = frames 11 to 15, t4 =

frames 16 to 20, t5 = frames 21 to 25, t6 = frames 26 to 30) to help minimize digitization error

yet to still give a time sequence of velocities for each video. We calculated the angle of attack

of the body (angle from *bill* to *body*) and of the tail (angle from *body* to *tail*), both relative to a

horizontal axis, using the coordinates from camera A.

We labeled the raw videos using the digital code from the original file name, and added

on the test bird number, date, and trial number. Therefore, we were blind to treatment while

analyzing the videos.

Sound Mapping

Before commencing flight trials, we confirmed that the speaker produced the intended

sound field. We used a (brand and model) sound meter to take sound measurements in dB SPL.

We took these measurements in every 0.4m x 0.4m x 0.4m cell, from ceiling to floor, in a 2m x

4m rectangular area (Figure 4A, 4B). The small difference between background sound fields during each season was due to the noise from an outdoor chiller in the summer. The sound level generated by the speaker was roughly the same in winter (81.9 dB SPL, SE = 0.93) as it was in summer (82.1 dB SPL, SE = 1.11).

Statistical Analyses

Due to time constraints, for this thesis project, all analyses were based on 10 of the 18 birds. We calculated three change variables (for velocity, body angle, and tail angle) by subtracting performance in the control flight from performance in each treatment flight (*Sound*, *MistNet*, *Both*). A negative value in the velocity change statistic meant a bird flew slower in the treatment relative to the most recent control flight. A positive value in any angle of attack change statistic indicated a larger angle of attack in the treatment flights relative to the control. We used repeated-measures ANOVAs to test our hypotheses, by comparing the differences in the change variables (velocity, body angle of attack, tail angle of attack) among treatments within each bird, at each time period (t1 through t6). When the overall repeated-measures ANOVA rendered a *P* < 0.05 we also inspected two specific contrasts: *Sound* vs *MistNet*, which helped us to interpret whether the presence of a sound field was perceived similarly to the presence of a barrier (i.e., mist net); and *MistNet* vs *Both*, which helped us understand whether the addition of a sound field in front of a barrier altered flight behavior further. Specifically, each contrast used partial eta-squared values to examine how large were the differences between these groups. A significant value when contrasting two groups (i.e. *P* < 0.05) indicated that the means between these two groups were significantly different. An effect size of greater

than 50% indicated that more than half the variation among treatments was due to the difference between these means. All analyses were performed with IBM SPSS Statistics v23 (IBM Corp.) employing two-tailed tests of probability.

Results

Within-individual change in flight velocity (relative to the most recent control flight for each bird) did not differ reliably among treatment groups when the birds were 2m away from the frame (and barrier) (i.e., at t1 and t2 where the repeated-measures ANOVA p-value > 0.05, Table 1a, Figure 5a). As birds approached the frame the *MistNet* (mist net only) and *Both* (mist net + sound) treatments slowed down the birds (t3 through t6, $P < 0.05$). However, when birds were closest to the wooden frame (t6) the presence of a sound field in front of a mist net slowed down birds substantially more than the presence of the mist net alone (effect size = 0.548, Table 1a, Figure 5a). Throughout the entire time sequence of flight, the Sound treatment alone had negligible effects on flight velocity (Figure 5a) whereas the *MistNet* treatment did slow down the birds at t3 and t4 (Table 1a, Figure 5a). Hence, it would appear that the sound field alone is not perceived as a barrier in the same manner as a mist net. However, the addition of a sound field in front of a mist net dramatically reduces flight velocity close to the time of contact with the barrier (i.e., at t6).

Treatment group did not affect within-individual change in body angle of attack for the initial periods of flight (t1 through t4, where the repeated-measures ANOVA p-value > 0.05, table 1b, Figure 5b). However, as the birds experienced the intense sound field at t5, body angle of attack increased in the *Both* treatment (Figure 5b). This difference was significant

16

between *Mistnet* and *Both* (p = 0.011) with a strong effect size (0.0527). When the birds were closest to the mist net (t6) the sound field resulted in a very large increase in body angle of attack relative to birds' reactions to the mist net alone (effect size = 0.694, Table 1b). This alteration of body position was consistent with the birds' decrease in velocity (Figure 5a). Throughout all time periods, the *Sound* treatment had no discernible effect on body angle of attack (Figure 5b). Additionally, there were no notable differences in body angle of attack between the *Sound* and *MistNet* treatments (Table 1b), indicating that the birds did not substantially alter their body angle of attack in the presence of the mist net alone. However, if a sound field was in front of the mist net then birds made large changes to their body posture.

Similarly to the body angle results, birds did not change their tail angle of attack during the initial periods of each flight trial (t1 through t4, where the repeated-measures ANOVA p-value < 0.05, Table 1c, Figure 5c). However, once birds reached the center of the sound field (t5) and approached the wooden frame (t6) there were large differences among treatment groups. Although there was no systematic change in tail angle of attack during the *Sound* treatments, the *MistNet* treatment induced an increase in tail angle (t6, effect size = 0.501, Table 1c) relative to the *Sound* treatment. This pattern indicates that the sound field alone was not perceived as a barrier similar to the mist net alone. However, when the sound field was presented in association with the mist net there was an even larger change in tail angle of attack beyond that induced by the mist net alone (t6, effect size = 0.783, Table 5c). Therefore, the sound field appears to influence tail angle of attack only if it is associated with a barrier. These changes in tail angle of attack were consistent with the decreases in flight velocity (Figure 5a).

Discussion

Our results indicate that in the presence of a visible barrier, an intensely audible sound field caused birds to slow down their flight and alter body position (Figure 5). Specifically, birds reduced their flight velocity by more than half (effect size = 54.8%) when the Acoustic Lighthouse was placed in front of a mist net, compared with their flight velocity when the sound field was not present. In support of this deceleration, birds also had highest angles of attack relative to their controls in both body (Figure 5b) and in tail (Figure 5c) as they progressed down the corridor in the *Both* treatment.

There are many implications for a bird's flight and collision risk that are associated with a reduction in flight velocity. A reduction in flight velocity may allow birds more time to process visual stimuli and respond more appropriately to manmade obstacles in their environment (Martin 2011). Birds and other animals such as mollusks and also insects, use this flow-field information, known as optic flow, to determine the distance between themselves and objects in their path (Gibson 1961, Lehrer et al. 1998, Martin 2011). When the eye of an animal, such as a bird, moves through space, objects that are nearer to the animal appear to move faster than more distant objects. The velocity on the retina at any point is given by an equation :

$(d\alpha/dt) - V \sin \alpha/d$

where *d* is distance, *V* is the bird's velocity, α is the angle between the object's direction and where the bird is going, and *dα/dt* is the angular velocity of the object as seen by the bird's eye (Land 1999). Because the velocity a bird travels is a factor in how birds gauge distances to objects in front of them, at slower velocities birds may be better able to integrate optic flow into their cognitive processes. Our results suggest that sound can potentially give birds in flight more time to include visible hazards in their flow-field as they fly.

Birds who fly slower in front of visible barriers could potentially have enough time to plan to avoid those barriers. Just as optic flow is used to gauge distance information, birds use optic flow to plan their flight trajectory and to help avoid collision with objects in a cluttered environment (Bhagavatula et al. 2011), which is known as reactive path planning (Lin et al. 2014). An example of a cluttered environment where birds need to use reactive flight planning is at a wind farm, where birds have to navigate around grids of turbines and their blades. The sooner birds can see turbine blades, the more planning they can put into avoiding them. Studies show that during planning of object avoidance, birds weigh their obstacle negotiation strategies (Williams and Biewener 2015). Decreasing speed, therefore, allows birds to have more time to determine how to safely navigate around objects they are approaching. This extra time for planning should be useful on a wind energy farm with many turbines to fly around, or through a cluttered urban environment with multiple buildings, telephone poles, wires, and radio towers, etc.

Our results on flight velocity go hand-in-hand with our results for body angle changes in each treatment. For the beginning of experimental trial flights, (i.e. t1-t4), birds' body angle of

attack was similar to their angles in the control flights (Table 1b, Figure 5b). However, when birds reached the sound field in the presence of the mist net, in treatment *Both*, they greatly altered their body angles (Figure 5b). Overall, the change induced by the Acoustic Lighthouse in front of a barrier was approximately 20° higher than in any other treatment relative to its control (Figure 5b). Since birds use their wings to slow down (Videler 2005, 226-227), it is likely the birds in our study decelerated by using their wings as air brakes, which would cause the corresponding increase in the body angles of attack. This significant increase in angle of attack in the *Both* treatment relative to its control, and not in *MistNet* or *Sound* treatments relative to their control, (Table 1c) further supports birds actively tried to slow down in the presence of sound in front of a visible barrier.

Our speculation is that body angle of attack did not change over time in the *MistNet* treatment (Figure 5b) possibly because there was no additional stimulus to the birds other than the mist net itself. We speculate that similar to when collisions happen in the field, the birds did not have enough time or focus to realize the mist net's hazard potential and adjust their body angles of attack in a way that could start to facilitate evasion. For example, while birds in the *MistNet* treatment generally flew at 5 degrees higher body angle of attack relative to their control than birds in the *Sound* treatment relative to their control (Figure 5b), this difference did not change as the birds advanced down the corridor. In other words, the presence of a visible barrier itself did not cause any change in their body angle of attack as birds advanced toward the object. It was only after the addition of sound at time block 5 (t5), in the *Both* treatment, that the birds increased their body angle of attack as they flew toward the visible object (Figure 5b). The reason why birds flew slower initially in treatments containing the mist

20

net (i.e. *MistNet* and *Both,* Figure 5a*)* was possibly because birds initially noticed the mist net, but did not recognize it as a complete barrier. This could be due to the wide lines on the net, known as trammel lines, which may have appeared to the birds to contain gaps large enough to fly through. We speculate that without further stimulus to draw their attention to the mist net, their velocity and body angle of attack remained relatively unchanged as they advanced down the corridor in the *MistNet* treatment (Figure 5a, 5b). However, when birds encountered sound in the *Both* treatment, the sound prompted them to slow down and change their body angles of attack, and we speculate it was because the sound caused the birds to become more alert to what was in front of them. We speculate the Acoustic Lighthouse, therefore, caused birds to become more alert in front of the visible barrier and to take action to begin to avoid the barrier (i.e. slow down and increase body angles of attack). Future studies that measure gaze direction in front of a visible object with and without sound could test this idea.

Because birds did not substantially increase their angles of attack and slow down in the *MistNet* treatment like they did in the *Both* treatment*,* our results suggest birds respond more appropriately (e.g. slow down, or increase their angles of attack) to a hazard in the presence of sound than without sound. There are many implications to this finding. For example, a positive change in body position, with the head tilting back and the feet coming forward, enables a bird to increase its lift and drag to slow down (Thomas 1996). Lift, or the force generated by a flying bird's wings, lifts a bird up in the air, while drag is the force acting against the bird as it flies forward in air (Videler 2005, 69-72). An increase in drag works to slow down a bird, while an increase in lift increases a bird's maneuverability. Therefore, our results indicate sound impacts the body angles of flying birds to increase their lift, enables birds to slow down, and makes

birds more potentially maneuverable. Maneuverability is defined as a bird's ability to change

its speed and direction of movement (Dudley 2002). Maneuverability of a bird in flight can

decrease its collision susceptibility by increasing its ability to avoid objects (Bevanger 1998,

Drewitt and Langston 2008, Janss 2008). Additionally, birds are able to redirect their

aerodynamic forces and shift between flight modes through altering their body angle (Berg and

Biewener 2010).

An increase in body angle of attack likely has consequences beyond adjustments in flight

velocity and agility. Some bird species (e.g. cranes and bustards) have an extremely limited

vertical extent of their binocular vision. For example, a kori bustard's vertical binocular vision

covers just 60 degrees (Martin 2007). In comparison, a human's binocular vision has a vertical

extent of 135 degrees. For species with a limited vertical binocular extent, peering downward

while flying, moving their heads in pitch (beak up or down) and yaw (beak moving left or right),

introduces blind spots in the direction of travel (Martin and Shaw 2010, Martin 2011). For these

species, an upward lifting of the head can effectively remove these blind areas. Therefore,

increases in angles of attack can potentially serve to remove blind spots and allow birds with a

limited vertical binocular field to see what is in front of them.

Similar to our results on body angle changes, our results on tail angle changes also

support that sound makes birds more maneuverable in front of a visible barrier. During the last

half of their flights, birds increased their tail angles of attack more in the *Both* treatment than in

the other two treatments (see Table 1c, Figure 5c). These differences were most pronounced

as the birds encountered the Acoustic Lighthouse sound field, which resulted, relative to

control flights, in a 50° change in tail angle of attack at the sound (t5) and a 65° change in tail angle of attack at the mist net (t6) (Figure 5c). These results complement our observations of flight velocity and body angle of attack, as an increase in tail angle of attack is a mechanism by which the birds can increase drag and help to slow down their flight (Thomas 1993, 1996b). Birds also use a large angle of attack of their tail to remain balanced during low speeds and to help generate lift (Thomas 1993, 1996a, 1996b). Lift allows a bird to climb in vertical height, and to stay aloft at slow speeds (Ellington 1991). Our results suggest that in the presence of a visible strike surface, birds use their tails to fly slower, and to stay aloft at a moderately slower speed. However when they experience sound in the presence of a visible structure, the increase in the tail angle of attack matches and enables their decrease in velocity (Figure 5a, 5c). The *MistNet* treatment also saw an increased tail angle of attack relative to its control, which increased slightly as the birds flew down the corridor (Figure 5c). However, the increased tail angle of attack seen in the *Both* treatment relative to its control at t5 and t6, was significantly larger than any increased tail angle of attack in either of the other treatments. The more modest increase in the tail angle of attack in the *MistNet* treatment matches the modestly slower velocity seen in birds in the *MistNet* treatment (Figure 5a). It is most likely birds in the *MistNet* treatment increased their tail angle of attack from approximately 7° higher than their control at t1, to approximately 20° higher than their control at t6. This change of approximately 13° suggests birds used their tails to fly slower in the *MistNet* treatment than they did in the *Sound* treatment. But it is a far cry from the approximately 56° change in tail angle of attack between t1 and t6 seen in birds flying in the *Both* treatment. Therefore, the added sound in the *Both* treatment made birds increase their tail angle of attack beyond just

23

that which was necessary to maintain slower speed, and instead increased their tail angles of attack sharply enough to help cause the deceleration in velocity we saw in birds in the *Both* treatment.

There are many useful applications to changes in angles of attack before hazardous objects. For example, increases in angles of attack like we saw in our study change the body posture of flying birds. Naturally, birds usually fly into things head-first. This position increases their chance of death, as the most common way a bird dies in a collision is by intracranial hemorrhaging (Klem 1990).   However, a mechanism that changes a bird's body posture in front of structures can potentially cause birds less serious harm. Birds flying with higher angles of attack, e.g. with the head rotated back and the feet thrust forward, are more likely to hit structures feet-first instead of head-first. Hitting feet-first means birds undergo less serious injury. Therefore, sound may have the potential to decrease mortality even when birds do collide with structures. Additionally, because birds fly slower in this position (i.e. they cannot fly at cruising speed at a high angle of attack), birds colliding with objects in this position would also hit with less force, resulting in less damage to them and potentially in less damage to the object(s) as well. When a flying bird's body is stopped by an object, such as a building or cell phone tower, the impact the bird withstands from colliding into the object matches its dynamic energy. The dynamic energy of a flying bird is equal to half its mass multiplied by its velocity-squared (Impact Force 2016). Therefore, in a collision event, how fast the bird is moving contributes to how much damage the bird suffers. As birds in our study halved their flight velocity in the presence of the sound field (Table 1a), this indicates that birds flying in the presence of sound strike a visible barrier with less force, and sustain less physical damage as a

result. For example, a Golden Eagle weighing 4.26 kg and flying at an average cruising speed of 14.2 mps (Kirschbaum and Ivory 2002) stopped completely by a wind turbine would experience an impact force of 1409 N during the collision (R Nave in press). The same bird flying at half the speed completely stopped by a wind turbine would experience an impact force of 353 N. Biologically this is still a very large impact, and a bird weighing 4.26 kg would not survive it. However, this suggests that when velocity is decreased by 50%, the impact force for a bird of this size and speed would be decreased by 75%. An impact force of 353 N may not damage a structure as much as a collision four times greater, resulting in less costs to the industries that own or operate the structures birds fly into. Furthermore, the Acoustic Lighthouse slowed down birds by 50% in 0.48m. In field conditions where the Acoustic Lighthouse is placed further out, a 50% speed reduction can potentially rapidly drive down the impact force during bird collisions. For example, if the 4.26 kg Golden Eagle initially at cruising speed of 14.2 mps encounters the Acoustic Lighthouse and slows down by 50% every half a meter, within a mere 1.5 meters the bird would be flying so slow (1.78 mps) it would have to stop, or collide into a structure with 22 N impact force. In under 2 meters, the bird's impact force would be less than 2% of its impact force had it collided without any reduction in speed. In addition to decreasing the damage to structures, depending on flight speed, body positioning and whether or not the collision structure itself suffers any damage and if it completely stops the bird, reductions in velocity may give some species the ability to survive a collision event. We expect that the combination of a less-fatal collision position coupled with a less forceful impact together could increase birds' chances of survival from collision, and that slowing birds down will result in less damage to structures.

Of course, it's not just one bird that flies into structures. Many times, it is whole flocks

of birds that fly into communication towers, buildings, windows, and wind turbines. We

examined the responses of individual birds to our treatments. It would be ecologically relevant

to examine the responses of a flock of birds to similar treatments. It is possible that the results

we saw with birds flying singly would be matched or more pronounced in birds flying in flock

formation, due to the collaborative nature of flocking. A flock of birds can form either a cluster

or a line as they fly together (Bajec and Heppner 2009). Cluster formation is a three-

dimensional flocking shape common to many birds. It is typically seen in smaller bird species

such as Dunlin (*Calidris alpina*) and other migrating shorebirds (Bajec and Heppner 2009), and

some species interchange between cluster and line formation (Piersma et. al 1990). Birds flying

in a cluster are able to execute rapid responses to changes in their environment, such as

turning within 120 ms (Davis 1980). They achieve this impressive synchronous activity because

each bird follows simple behavioral rules in accordance to its neighbors (Okubo 1986, Reynolds

1987, Heppener and Grenander 1990). These simple rules are to avoid collision with nearby

neighbors, match velocity to nearby neighbors, and stay close to nearby neighbors (Reynolds

1987). Given that birds flying in cluster formation respond to the velocity and proximity of their

neighbors, and sound slows down birds in the presence of a visible object, sound may also work

to slow down entire flocks of birds. In other words, if one bird slows down, this should have an

impact on the rest of the flock, because a flock acts as its own behavioral unit (Kennedy and

Eberhart 1995; Bajec and Heppener 2009). Therefore, given the cohesive and collaborative

nature of birds flying in cluster formation, it is reasonable to expect that in a flock setting, the

whole flock may react in tandem to the reactions of the birds who encounter the sound in front

of a visible object. It merits further study in the field to determine if sound can help divert

entire flocks from collision with visible objects.

In addition to decreasing the force of impact and to potentially altering the flight paths

of flocks, sound can potentially help address the three main reasons birds fly into objects. Birds

either do not see visible objects (such as towers or power lines), they are attracted to the

objects (such as lights), or they do not see objects which are not visible to them (e.g. windows).

The Acoustic Lighthouse may have strong mitigative properties for collisions with visible

structures birds commonly fly into. For example, birds frequently do not see power lines and

fly into them, dying from the collision or from electrocution (Bevanger 1998, Shaw et al. 2010).

In fact, collision with power lines kills millions of birds per year (Erickson et al. 2005) and

particular species can be prone to flying into them depending on their morphology and flight

behavior (Drewitt and Langston 2008). Some species that frequently collide with power lines

simply lack the visual field necessary to see power lines. These species, such as cranes and

bustards, have limited binocular viewing, and may not see power lines as they fly (Martin 2011,

Silva et al. 2014). For these species, the Acoustic Lighthouse could be used to help increase

their body angle of attack, which would raise the head and potentially put the power lines into

the binocular field of view (Martin 2011). This could enable the bird to take appropriate action

to avoid the power lines. We would expect similar mitigative effects from noise placed in front

of other visible structures, such as communication and cell phone towers, and fences (Baines

and Summers 1997).

Another type of visible objects that birds collide into, wind turbines, do make noise. But the noise they generate is largely drowned out by background noise, so as birds fly toward wind turbines, they generally do not hear them (Dooling 2002). The Acoustic Lighthouse could help make wind turbines more apparent to birds by serving to acoustically warn them of their presence. For example, a wind turbine's rotating blades are inaudible to a flying bird starting at 25 meters from the blades (Dooling 2002), and, naturally, they do not make any noise whenever the turbine blades are not rotating. This means that birds flying within 25 meters of blades do not hear the blades. A research study showed that when turbine blades emit a whistling sound, this sound, higher than the sound from the blades themselves, remained audible to birds until they were 15 meters from the blades (Dooling 2002). The whistle therefore potentially gave birds 10 more meters in which to hear the blades, increasing the chance they would see them. It was hypothesized that louder blade noises would result in fewer bird fatalities (Dooling 2002). In our study, we have demonstrated how this might occur. In the field, birds could encounter a loud warning sound set within the 25m before the blades (Figure 6). Our study examined a distance close to 0.5m before the strike surface. Figure 6 shows a possible set-up featuring the speakers set on the turbine itself. The speakers could also be set further out within the 25m from the blades, at a distance determined relative to bird species and flight speed. The cruising speed of birds in the field will vary according to species (Alerstam et al. 2007). For example, while gulls fly between 10 and 20 m/s, hawks fly below 15 m/s (Alerstam et al. 2007). Therefore, the locations of the Acoustic Lighthouse in the field may also depend on which species it targets.

Another possible application for the Acoustic Lighthouse is to help birds maneuver around objects while flying in low-light conditions. We did not test for what happens when birds are flying in low-light conditions, but we have some predictions about how sound may impact birds with nocturnal vision or while flying in low-light conditions. Nocturnal vision capability in birds depends on rod densities and rod : cones ratios (Rojas et al. 1999). Therefore, how visible structures are to birds in low-light or night-time conditions is species-variable. For birds with nocturnal vision, it is possible that the Acoustic Lighthouse could potentially draw their attention to towers and other objects in front of them as they fly in the dark. This could be potentially important for the millions of migratory songbirds that migrate every year in the dark, using their night vision to help guide them (Mouritsen et al. 2005). The sound field is less likely to help birds focus on towers during strongly inclement weather, however, since the low visibility of objects during inclement weather is also a factor in collision (Longcore et al. 2013). However, our results suggest sound can help decrease flight speed and improve maneuverability in instances where the birds can still see the towers as they approach. So in low-light conditions which allow for some visibility, we expect sound to aid birds, especially those with good night vision, in avoiding collision. To test this idea, a future study could apply our treatments in lab-controlled low-light conditions.

When flying at night or in low-light conditions, birds are attracted to the lights on towers, called obstruction lights. They use these lights, particularly the red, steady-burning ones, for navigational reference, especially in low levels of light or inclement weather (Gauthreaux and Belser 2006, Gehring 2010, Patterson 2012, Longcore et al. 2013). Once they reach a light, they can become confused and circle the light, rather than continue to fly on

(Gauthreaux and Belser 2006). This circling increases the chance of collision with the tower, and uses up migrating birds' resources, often ending in exhaustion and death for the birds (Patterson 2012). Future field tests or lab studies on how lights and sound may interact to impact birds would help elucidate how sound would potentially interplay with another visual attractant in the presence of a visible barrier. For example, if the sound field increases visual attention, it might increase attractiveness of lights and increase collisions with structures that have lights on them. More information is needed on how birds flying in night-time conditions respond to both lights and sound. A future study could include lights as a treatment group, for example, and the study could be run in low-light conditions when birds are most attracted to lights/lights are most used. It is prudent to note that discontinuing lights or changing their color from red to white and making them blink rather than shine steadily (Gehring et al. 2009, Patterson 2012) has been shown to reduce bird strike by 50-71% (Gehring et al. 2009) and we advocate these measures whenever possible.

Lights on towers are not the only lights that attract flying birds. Birds also fly toward lights on inside buildings, where they commonly crash into windows. They also fly into windows because they see the reflection on windows as extensions of their environment (Klem 2009). Our results show that birds flying in the presence of sound alone do not slow down (Figure 5a). So, given that birds commonly don't recognize windows as barriers, we expect that birds flying toward windows in the presence of sound will still fly into them at the same speed. However, if windows are adorned by markers, the windows become visible to birds. Our results suggest that window markers that have been shown to be successful at reducing bird strike in the field will be even more successful with the further addition of sound. Examples of such

markings include parachute cord (Klem and Saenger 2013) and specifically-spaced stripes or patterns (Rössler 2015). These markings do not need to be visible to humans and can be visible to birds if they are UV-reflecting or UV-absorbing, and have been shown to reduce bird strike to windows by up to 50% (Klem 2009). In effort to further decrease bird strike at windows, the Acoustic Lighthouse could be used in tandem with these adornments. By making the window visible, and then putting sound in front of it, birds could potentially see the window markings sooner and respond appropriately, similar to how they responded in the *Both* treatment in our experiment. Birds are more likely to avoid things they can both see and hear (Dooling 2002), and it is probable that combining two mitigative measures at one location could result to collectively drive down bird strike instances more than either one alone.

Our results indicate that sensory ecology considerations to mitigative measures against bird strike can be successful and should be researched further, both in the lab and field. In order to examine immediate changes in velocity and body posture, we examined our sound field placed immediately in front of the strike surface. Because the sound field was so close to the mist net (approximately 0.5 m), the birds in our study could not avoid the mist net entirely. In order to examine less immediate changes in velocity, body posture, and collision avoidance, future studies should be undertaken with a larger distance between the sound and a visible benign barrier. We intend to explore how a sound field projected tens or hundreds of meters in front of a strike surface influences the probability of collisions. We predict that the decreases in velocity and increases in angle of attack we observed in our study will lead to reduced probability of collision and less mortality if strike does occur.

Due to differences among bird species in morphology, behavior, conservation status, geography and even protective legislature, it is likely that there is no single successful mitigation strategy to the overall problem of bird strike. However, future successful mitigation strategies should adapt technology to the way impacted species experience the world. For example, field studies specific to barrier types (e.g. fences, power lines, wind turbines, communication towers, etc.) could focus on species that are known to collide with these structures. Field studies on power lines could examine species that frequently collide with them, such as water birds and pheasants (Bevanger 1998), and species reported to suffer electrocution at power lines, such as herons, harriers, and kites. Species of conservation concern, such as the little bustard (*Tetrax tetrax)*, could also be prioritized for future studies, as populations of these species are more sensitive to declines even if collisions are infrequent. Similarly, we could prioritize species that are known to die in large numbers because of collisions, such as species of neotropical migrant songbirds that die during migration because of collisions with buildings and towers (Longcore et al. 2013).

In conclusion, the results of this study show that when flying zebra finches encounter a loud sound field in front of a visible barrier, the birds slow their flight (relative to a control flight) by approximately 25% and concomitantly increase their body and tail angles of attack by 20° and 50°, respectively. This alteration of velocity and flight posture will likely increase birds' capacity to maneuver, due to increased tail drag and improved tail lift, and potentially afford them more time to react appropriately to their environment and plan object avoidance. Collectively, our results support the conclusion that a conspicuous sound can decrease birds' risk of striking a static surface/object.

Literature Cited

Alonso, J. C., J. A. Alonso, and R. Muñoz-Pulido (1994). Mitigation of bird collisions with
transmission lines through groundwire marking. Biological Conservation 67, no. 2: 129-134.

Arnold, T. W., and R. M. Zink (2011). Collision Mortality Has No Discernible Effect on
Population Trends of North American Birds. Plos One 6 (9): e24708.

Baines, D., and R. W. Summers (1997). Assessment of bird collisions with deer fences in
Scottish forests. Journal of applied ecology: 941-948.

Bajec, I. L., and F. H. Heppner (2009). Organized flight in birds. Animal Behaviour 78, no. 4 :777-789.

Barrientos, R., C. Ponce, C. Palacín, C. A. Martín, B. Martín, and J. C. Alonso (2012). Wire
marking results in a small but significant reduction in avian mortality at power lines: a
BACI designed study. Plos One no. 7 (3): e32569.

Berg, A. M., and A. A. Biewener (2010). Wing and body kinematics of takeoff and landing flight
in the pigeon (*Columba livia*). The Journal of experimental biology 213 (10): 1651-1658.

Berge, A., M. Delwiche, W. P. Gorenzel, and T. Salmon (2007). Bird control in vineyards using

alarm and distress calls. American journal of enology and viticulture 58, no. 1: 135-143.

Bevanger, K. (1994). Bird interactions with utility structures: collision and electrocution, causes

and mitigating measures. Ibis, 136: 412–425.

Bevanger, K. (1998). Biological and conservation aspects of bird mortality caused by electricity

power lines: a review. Biological Conservation 86(1): 67-76.

Bhagavatula, P. S., C. Claudianos, M. R. Ibbotson, and M. V. Srinivasan (2011). Optic flow cues

guide flight in birds. Current Biology 21 (21): 1794-1799.

Blokpoel, H. (1976). Bird hazards to aircraft. In Bird Hazards to Aircraft. Clarke.

Dale, L. A. (2009). Personal and corporate liability in the aftermath of bird strikes: a costly

consideration. Human–Wildlife Interactions. Paper 12.

http://digitalcommons.unl.edu/hwi/12

Davis, J. M. (1980). The coordinated aerobatics of dunlin flocks. Animal Behaviour, 28, pp.

668–673.

Dooling, R. J. (1980). Behavior and Psychophysics of Hearing in Birds. In Comparative Studies

of Hearing in Vertebrates, (A. N. Popper and R. R. Fay, Editors)   261–288.

Dooling, R (2002). Avian Hearing and the Avoidance of Wind Turbines. Report no. NREL/TP -500

-30844. Golden, CO: National Renewable Energy Laboratory.

Drewitt, A. L. and R. H.W. Langston (2008). Collision effects of wind-power generators and

other obstacles on birds. Ann. N.Y. Acad. Sci. 1134: 233–266.

Dudley, R. (2002). Mechanisms and Implications of Animal Flight Maneuverability.

Integrative and Comparative Biology 42 (1): 135–40.

Ellington, C. P. (1991) Limitations on animal flight performance. Journal of Experimental

Biology 160: 71-91.

Erickson, W. P., G. D. Johnson, and P. David Jr (2005). A summary and comparison of bird

mortality from anthropogenic causes with an emphasis on collisions. USDA Forest

Service Gen. Tech. Rep. PSW-GTR-191.

Font, V. (2016). Wind Energy Setting Records, Growing Still: The Wind Energy Outlook for

2016. Renewable Energy World.com. February 3, 2016.

http://www.renewableenergyworld.com/articles/2016/02/wind-energy-setting-records-growing-still-the-wind-energy-outlook-for-2016.html.

Garcia-del-Rey, E. and J. A. Rodriguez-Lorenzo (2011). Avian mortality due to power lines in the Canary Islands with special reference to the steppe-land birds. Journal of Natural History 45 (35-36): 2159–69.

Gauthreaux Jr, S. A., and C. G. Belser (2006). Effects of artificial night lighting on migrating birds. Ecological consequences of artificial night lighting (C. Rich and T. Longcore, Editors). 67-93.

Gehring, J. (2010). Studies of Avian Collisions With Communication Towers: A Quantification of Fatalities at a Self-Supported Rescue 21 Tower and a Test of Different Tall Tower Lighting Systems, 2008 and 2009 Progress Report.

Gehring, J., Kerlinger, P. and A. M. Manville (2009). Communication towers, lights, and birds: successful methods of reducing the frequency of avian collisions. Ecological Applications, 19: 505–514.

Hötker, H., K.-M. Thomsen and H. Jeromin (2006). Impacts on biodiversity of exploitation of renewable energy sources: the example of birds and bats – facts, gaps in knowledge,

demands for further research, and ornithological guidelines for the development of

renewable energy exploitation. Michael-Otto-Institut im NABU.

Hunt, W.G. (2002). Golden Eagles in a perilous landscape: predicting the effects of mitigation

for energy-related mortality. California Energy Commission Report P500-02-043F.

Hunt, W.G. and T. Hunt (2006). The trend of golden eagle territory occupancy in the vicinity of

the Altamont Pass Wind Resource Area: 2005 survey. California Energy Commission

Public Interest Energy Research Final Project Report CEC-500-2006-056.

"Impact Force" (2016). Engineeringtoolbox.com. N.p., Web. 23 May 2016.

Inglis, I. R (1980). Visual bird scarers: an ethological approach. Bird problems in agriculture:

121-43.

Janss, G. F. E. (2000). Avian mortality from power lines: a morphologic approach of a species-

specific mortality. Biological Conservation. 95: 353–359.

Jaroslow, B. N. (1979). Review of factors involved in bird-tower kills, and mitigative

procedures. No. CONF-790737-3.

Jaroslow, B. L (1979). A review of factors involved in bird-tower kills and mitigative procedures.

    SciTech Connect. Web. https://files.zotero.net/7060742733/6002087.pdf.

Jenkins, A. R., J. M. Shaw, J. J. Smallie, B. Gibbons, R. Visagie, and P. G. Ryan (2011). Estimating

    the impacts of power line collisions on Ludwig's Bustards, *Neotis ludwigii*. Bird

    Conservation International 21 (03): 303–10.

Kerlinger, P (2000). Avian Mortality at Communication Towers: Recent Literature, Research and

    Methodology. Review. United States Fish and Wildlife Service Office of Migratory Bird

    Management. http://training.fws.gov/Pubs9/avian_mortality00.pdf.

Kirschbaum, K. and A. Ivory (2002). *Aquila chryaetos,* Golden Eagle. The Animal Diversity Web.

    University of Michigan Museum of Zoology.

Klem, D., Jr. (1989). Bird-Window Collisions. The Wilson Bulletin 101(4):606-620.

Klem, D., Jr. (1990). Collisions between birds and windows: mortality and prevention. Journal

    of Field Ornithology 61.1: 120-128.

Klem, D., Jr. (2004). Avian Mortality at Windows: The Second Largest Human Source of Bird

    Mortality on Earth. Proceedings of the Fourth International Partners in Flight

Conference: Tundra to Tropics, Acopian Center for Ornithology, Department of

Biology, Muhlenberg College, Allentown. Allentown: Muhlenberg College. 244-51.

Klem, D., Jr. (2009). Preventing Bird-Window Collisions. The Wilson Journal of Ornithology

121(2): 314-321.

Klem, D., Jr., K. L. DeGroot, E. A. Krebs, K. T. Fort, S. B. Elbin, and A. Prince (2012). A second

critique of 'collision mortality has no discernible effect on population trends of North

American birds'." Editorial. Plus One.

http://journals.plos.org/plosone/article/comment?id=info:doi/10.1371/annotation/173

7a522- 841f-49b2-b31b-c46b410edd53.

Klem, D., Jr., and P. G. Saenger (2013). Evaluating the effectiveness of select visual signals

to prevent bird-window collisions." The Wilson Journal of Ornithology 125 (2): 406–11.

Land, M. F. (1999) Motion and vision: why animals move their eyes. Journal of Comparative

Physiology A 185, 4: 341-352.

Larkin, R. P., and B. A. Frase (1988). Circular paths of birds flying near a broadcasting tower

in cloud. Journal of Comparative Psychology 102, 1: 90.

Lee, A (2013). VirtualDub. Computer software. Version 1.10.4. Virtualdub.org.

http://virtualdub.com/.

Lekuona, J. M., and C. Ursua (2007). Avian mortality in wind power plants of Navarra (Northern

Spain). Birds and wind farms: risk assessment and mitigation. Quercus. 177-192.

Lin, H., I. G. Ros, and A. A. Biewener (2014). Through the eyes of a bird: modelling visually

guided obstacle flight. Journal of The Royal Society Interface 11, 96:20140239.

Longcore, T., C. Rich, and S. A. Gauthreaux (2008). Height, guy wires, and steady-burning lights

increase hazard of communication towers to nocturnal migrants: a review and meta-

analysis. The Auk 125 (2): 485–92.

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, et al. (2012).

An estimate of avian mortality at communication towers in the United States and

Canada.” Plos One 7 (4): e34025.

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, et al. (2013).

Avian mortality at communication towers in the United States and Canada: which

species, how many, and where?” Biological Conservation 158 (February): 410–19.

Loss, S. R, T. Will, and P. P Marra (2012). Direct human-caused mortality of birds:

improving quantification of magnitude and assessment of population impact.

Frontiers in Ecology and the Environment 10 (7): 357–64.

Madliger, C. L. (2012). Toward improved conservation management: a consideration of

sensory ecology." Biodiversity and Conservation 21 (13): 3277–86.

Manville, A. M. II., (1999). The ABCs of avoiding bird collisions at communication towers: the

next steps. Proceedings of the Avian Interactions Workshop, December 2, 1999, Electric

Power Research Institute (in press). http://nctc.fws.gov/resources/knowledge-

resources/bird-publications/tower-collisions.html

Manville A. M. II., (2005). Bird strike and electrocutions at power lines, communication

towers, and wind turbines: state of the art and state of the science - next steps toward

mitigation. In Bird Conservation Implementation and Integration in the Americas:

Proceedings of the Third International Partners in Flight Conference (R., C. John, R.

Terrell, Editors). Volume 2 Gen. Tech. Rep. PSW-GTR-191. U.S. Dept. of Agriculture,

Forest Service, Pacific Southwest Research Station: 1051-1064

Manville, A. M., II. (2009). Towers, turbines, power lines, and buildings: steps being taken by

the U.S. Fish and Wildlife Service to avoid or minimize take of migratory birds at these

structures. In Tundra to tropics: connecting birds, habitats, and people (T.D. Rich, C.

41

Arizmendi, D. Demarest, and C. Thompson, Editors). Proceedings 4th international

Partners in Flight conference. Partners in Flight: 262–272.

Marques, A. T., H. Batalha, S. Rodrigues, H. Costa, M. J. R. Pereira, C. Fonseca, M. Mascarenhas,

and J. Bernardino (2014). Understanding bird collisions at wind farms: an updated

review on the causes and possible mitigation strategies. Biological Conservation 179

(11): 40–52.

Martin, G. R. (2007). Visual fields and their functions in birds. Journal of Ornithology 148

(2): 547–62.

Martin, G. R., and J. M. Shaw (2010). Bird collisions with power lines: failing to see the way

ahead?" Biological Conservation 143 (11): 2695–2702.

Martin, G. R (2011). Understanding bird collisions with man-made objects: a sensory ecology

approach. Ibis 153, (2): 239-254.

Montoney, A. J., and H. C. Boggs (1993). Effects of a bird hazard reduction force on

reducing bird/aircraft strike hazards at the Atlantic City International Airport, NJ. In

Sixth Eastern Wildlife Damage Control Conference: 23.

Mouritsen, H., G. Feenders, M. Liedvogel, K. Wada, and E. D. Jarvis (2005). Night-vision brain

   area in migratory songbirds. Proceedings of the National Academy of Sciences of

   the United States of America 102, (23): 8339-8344.

Nave, R (in press). Work-Energy Principle. Hyper Physics. http://hyperphysics.phy-

   astr.gsu.edu/hbase/work.html#wepr.

Ogden, E. and J. Lesley (1996). Collision Course: The Hazards of Lighted Structures and

   Windows to Migrating Birds. Fatal Light Awareness Program (FLAP).

   http://digitalcommons.unl.edu/flap/3.

Patterson, J. W., Jr. (2012). Evaluation of New Obstruction Lighting Techniques to Reduce Avian

   Fatalities. Technical paper no. DOT/FAA/TC-TN12/9. Atlantic City International Airport:

   Federal Aviation Administration.

   http://www.tc.faa.gov/its/worldpac/techrpt/tctn12-9.pdf.

Paula, J., M.C. Leal, M. J. Silva, R. Mascarenhas, H. Costa, and M. Mascarenhas (2011). Dogs as

   a tool to improve bird-strike mortality estimates at wind farms. Journal for Nature

   Conservation 19 (4): 202–8.

Piersma, T., L. Zwarts, and J. H. Bruggemann (1990). Behavioural aspects of the departure of

    waders before long-distance flights: flocking, vocalizations, flight paths and diurnal

    timing. Ardea 78, (2): 157-184.

Rasband, W. (2006). ImageJ. Computer software. Version 1.4.3.67.

    http://imagej.nih.gov/ij/index.html.

Rogers, L. J. (2008). Development and function of lateralization in the avian brain. Brain Resarch

    Bulletin 76: 235–244.

Rojas, L. M., R. McNeil, T. Cabana, and P. Lachapelle (1999). Behavioral, morphological and

    physiological correlates of diurnal and nocturnal vision in selected wading bird

    species. Brain, Behavior and Evolution 53 (5-6): 227–42.

Rössler, M., E. Nemeth, and A. Bruckner (2015). Glass pane markings to prevent bird-window

    collisions: less can be more. Biologia 70 (4): 535–41.

Schaub, M., M. Kery, P. Korner, and F. Korner-Nievergelt (2011). A critique of 'Collision

    mortality has no discernible effect on population trends of North American birds'.

    Editorial. Plos One

    http://journals.plos.org/plosone/article/comment?id=info%3Adoi%2F10.1371%2Fannot

    ation%2F68b2f3ba-a22b-499c-ae55-4aaf7013e6b1

Loss, S. R., T. Will, S. S. Loss, and P. P. Marra (2014). Bird–building collisions in the United

    States: estimates of annual mortality and species vulnerability. The Condor:

    Ornithological Applications 116: 8-23.

Shaw, J. M. (2009). The end of the line for South Africa's national bird? Modelling power line

    collision risk for the Blue Crane. MS thesis. University of Cape Town, Cape Town.

Shaw, J. M., A. R. Jenkins, P. G. Ryan, and J. J. Smallie (2010). A preliminary survey of avian

    mortality on power lines in the Overberg, South Africa. Ostrich 81 (2): 109-113.

Silva, J. P., J. M. Palmeirim, R. Alcazar, R. Correia, A. Delgado, and F. Moreira (2014). A spatially

    explicit approach to assess the collision risk between birds and overhead power   lines: A

    case study with the Little Bustard. Biological Conservation 170: 256-263.

Slater, P. J. B. (1980). Bird behaviour and scaring by sounds. Bird problems in agriculture 105-

    114.

Smallwood, K. S., and C. Thelander (2008). Bird mortality in the Altamont Pass wind

    resource area, California. The Journal of Wildlife Management 72 (1): 215–23.

Summers, R.W. (1985). The effect of scarers on the presence of starlings (*Sturnus vulgaris)* in

    cherry orchards. Crop Protection 4: 520-528

Thomas, A. L. R. (1993). On the Aerodynamics of Birds' Tails. Philosophical Transactions of the

Royal   Society B 340(1294).

Thomas, A. L. R. (1996a). The flight of birds that have wings and a tail: variable geometry

expands the envelope of flight performance. Journal of Theoretical Biology 183(3):

237-245.

Thomas, A. L.R. (1996b). Why do birds have tails? The tail as a drag reducing flap, and trim

control. Journal of Theoretical Biology 183 (3): 247–53.

Veltri, C. J., and D. Klem (2005). Comparison of fatal bird Injuries from collisions with towers

and windows. Journal of Field Ornithology 76 (2): 127–33.

Videler, John J. (2005). Avian Flight. Oxford: Oxford University Press.

Williams, C. D., and A. A. Biewener (2015). Pigeons trade efficiency for stability in response

to level of challenge during confined flight. Proceedings of the National Academy of

Sciences 112, (11): 3392-3396.

Wind Power Report (2006). Report. London: ABS Energy Research.

http://www.windaction.org/posts/3973-abs-energy-research-wind-power-report-

2006#.Vy92F-TjXm4.

Wind Vision: A New Era for Wind Power in the United States (2012). Report.

http://www.energy.gov/sites/prod/files/WindVision_Report_final.pdf.

Figure Legends

Figure 1. A plan view of the flight corridor. 'A' denotes where Camera A was placed. 'B' denotes where Camera B was placed. The grey bar indicates sound-absorbing foam, which also covered the whole ceiling. Camera B was located near the edge of the Acoustic Lighthouse sound area. The white cage on the end box contained stimulus birds at all times.

Figure 2. A plan view of birds in bidirectional flight training. The training subject's flight was deemed a success when the bird flew from the start box to the end box similar to the path shown by the purple arrow 1, or when the subject flew from the end box to the start box similar to the path shown by red arrow 2.

Figure 3. Schematic of a bird showing how a bird was seen from camera A. For each bird, we collected *x* and *y* coordinates for three points on the camera A videos: bill, body, and tail (see text for more information). We also digitized the bill point on the camera B videos to collect a *z* coordinate.

Figure 4A and 4B. A plan view of the flight corridor showing the sound field at time blocks t1 through t6, with the Acoustic Lighthouse, signified in red, on in (a) "summer" and (b) "winter" sound fields. Each individual square within the yellow 2.0m x 4.0m rectangle measured 0.40m x 0.40m and is scaled.

Figure 5A, 5B, and 5C. Within-individual, relative to the most recent control flight, in flight parameters during the six time periods of each flight trial (t1 to t6). (a) Mean (±SE) velocity, (b) mean (±SE) body angle of attack, (c) mean (±SE) tail angle of attack. The center of the sound field was experienced at t5 and the wooden frame was immediately after t6.

Figure 6. Schematic showing the possible locations for the Acoustic Lighthouse surrounding a wind turbine. The red triangle at 25m signifies the distance at which a wind turbine becomes inaudible to birds. The proposed location of the sound beams from the Acoustic Lighthouse

speakers is represented in orange, originating from the nose of the turbine (the rotor hub) and covering the width and height of the turbine blades and the airspace through which they spin (the rotor swept zone).
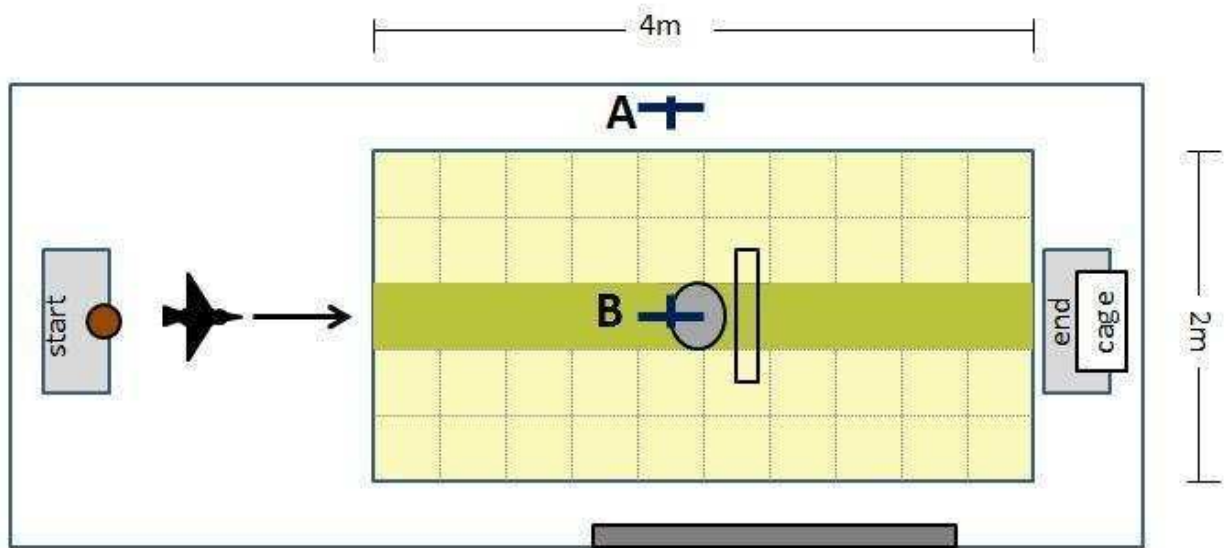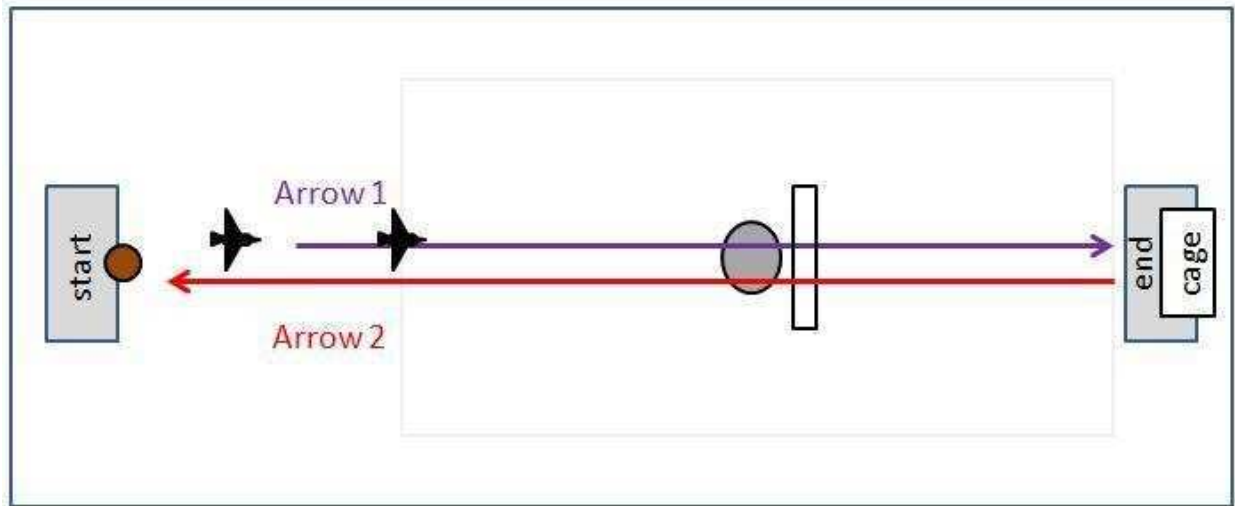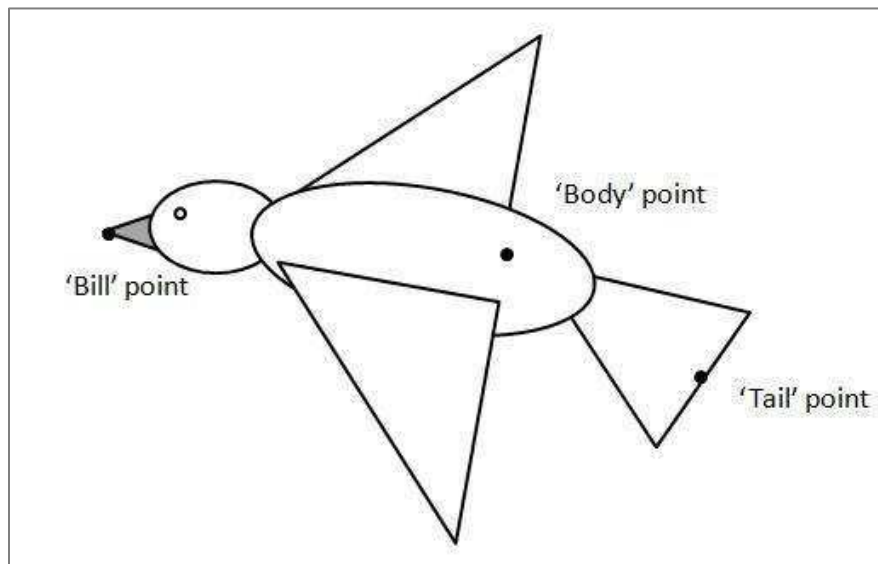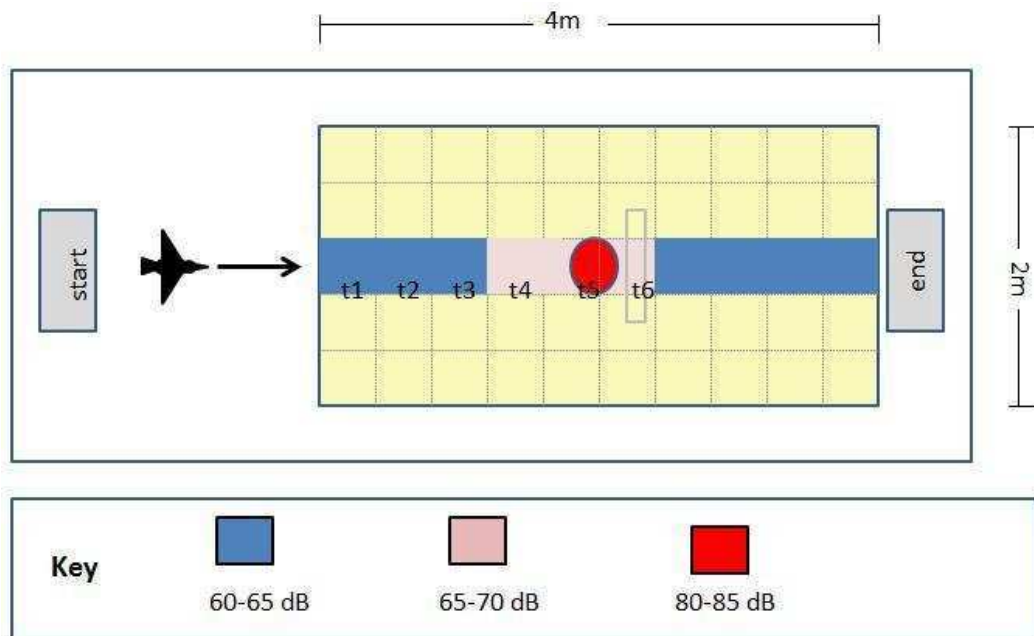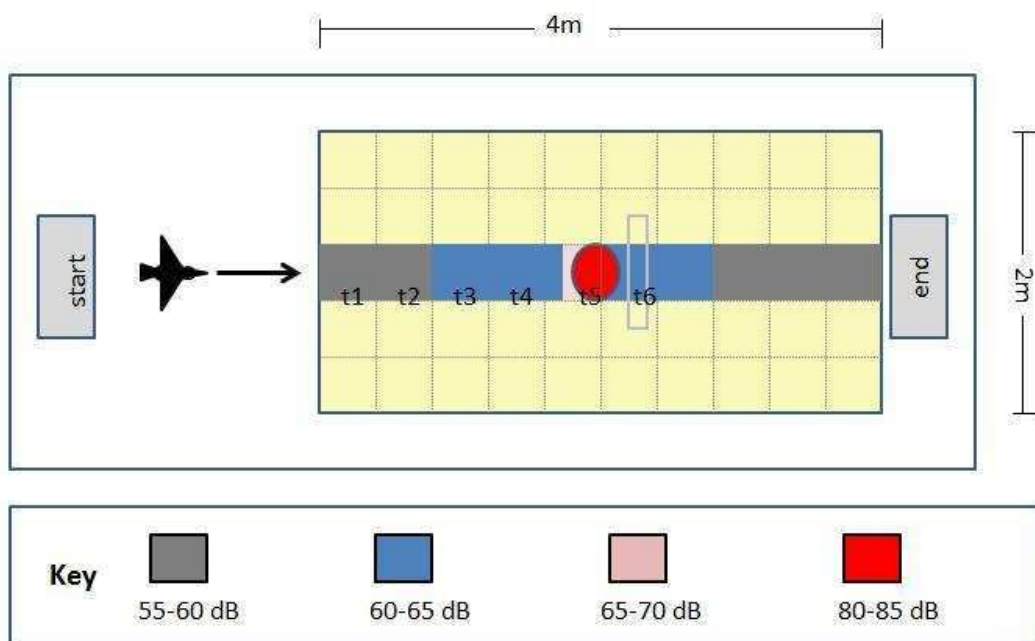
Figure 1.

Figure 2.

Figure 3.

Figure 4.

(a)

(b)

Figure 5.

(a)

(b)

(c)

Figure 6.

Sound beams projecting outward

25m

(Not drawn to scale)
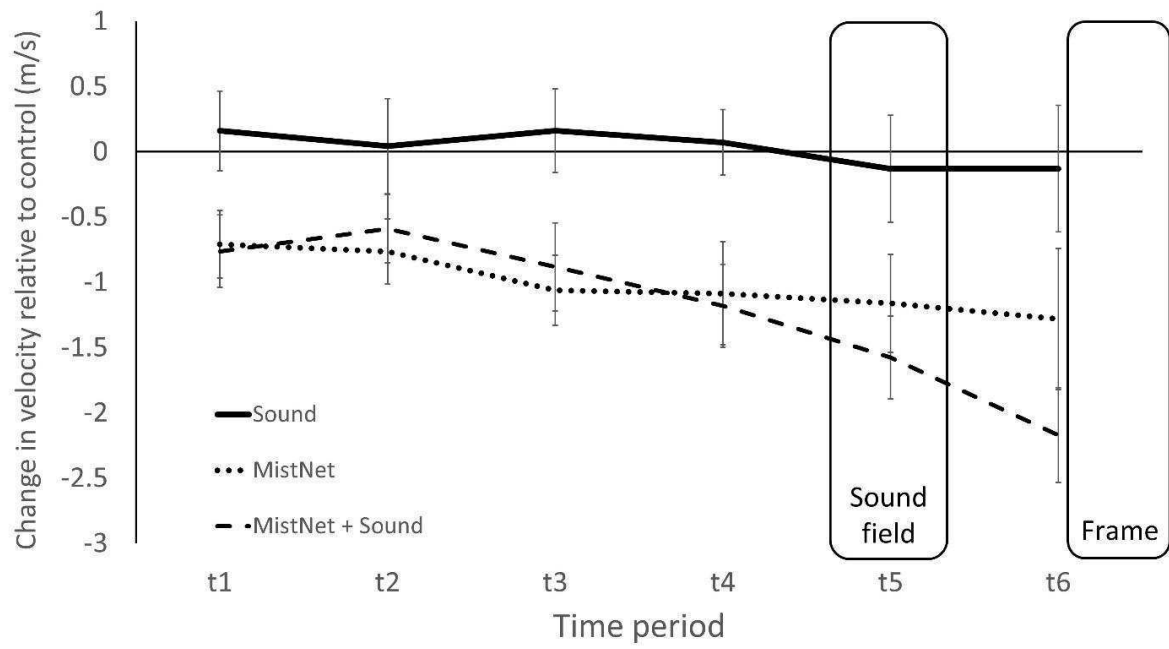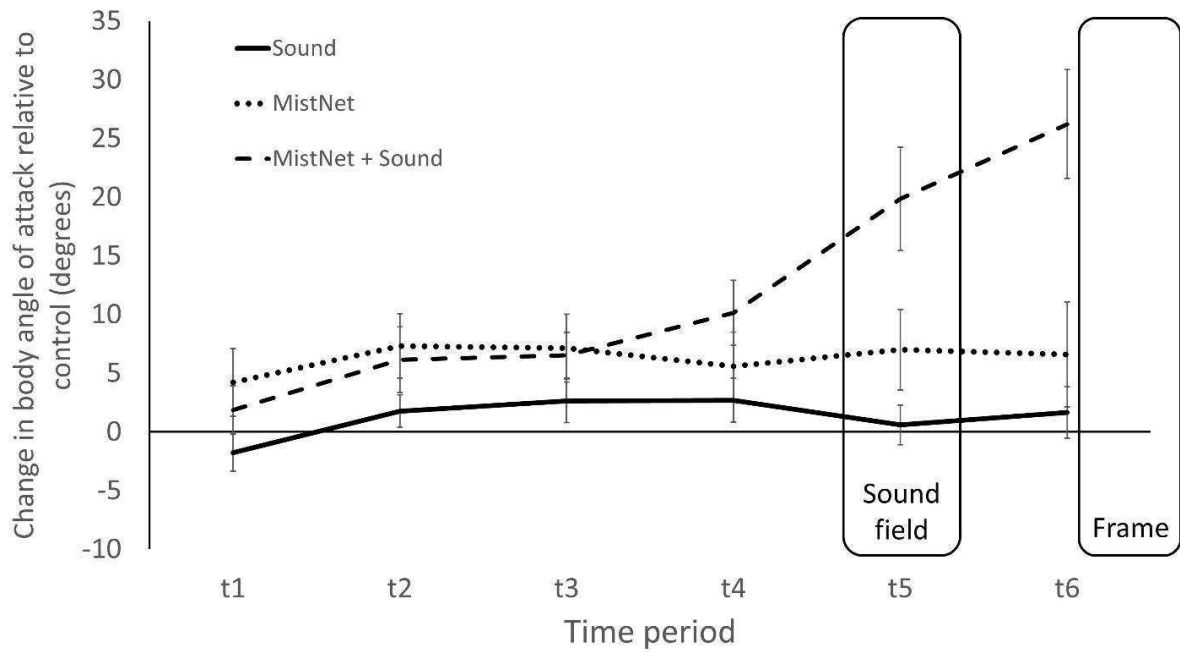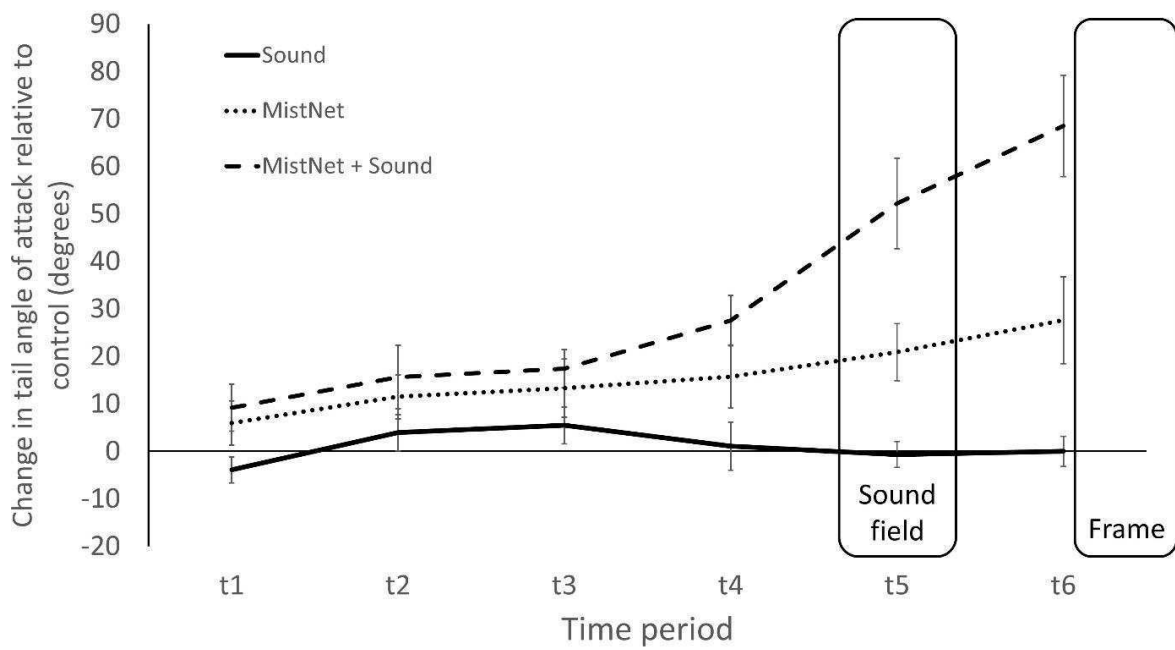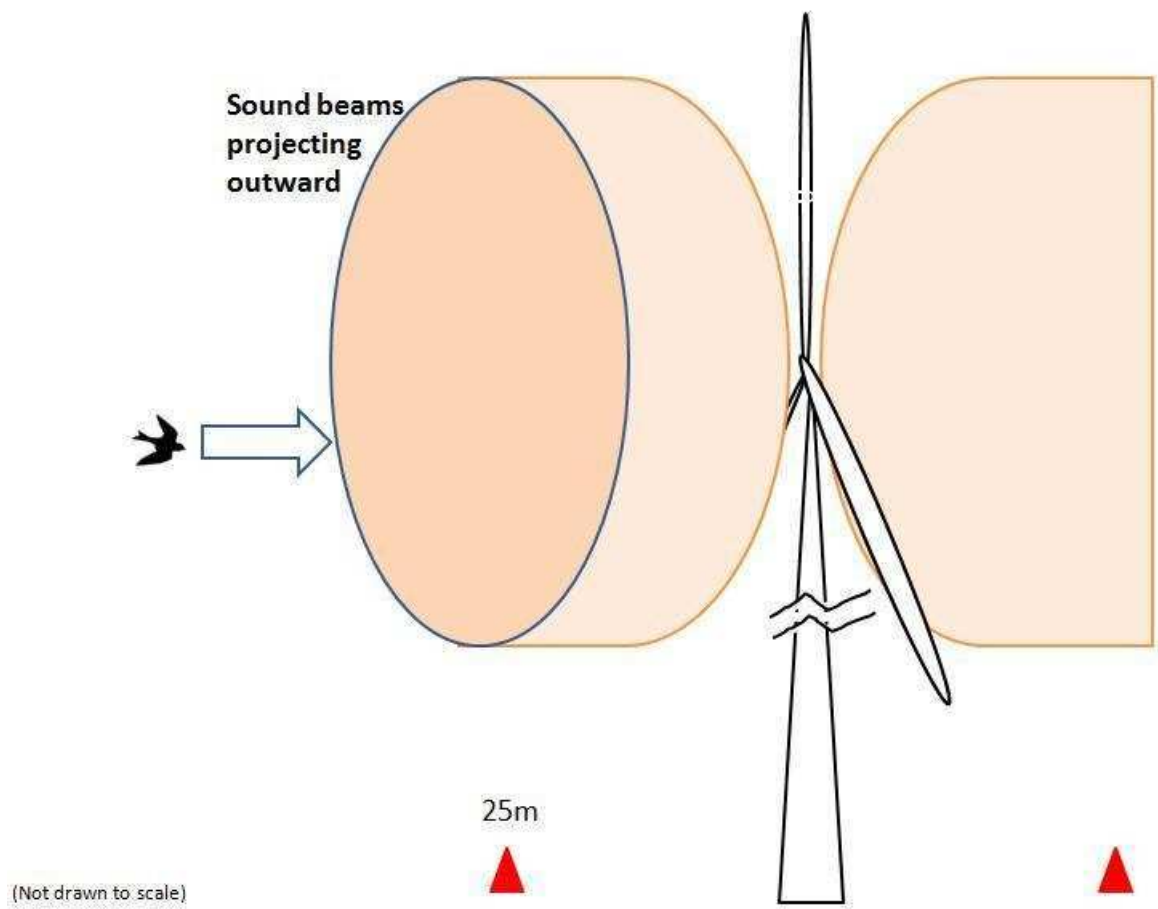
Table 1. Statistical summaries from repeated-measures ANOVAs that compare differences in within-individual change (relative to control flights) in flight parameters among treatment groups, with contrasts specified as appropriate (i.e., when overall ANOVA $P < 0.05$). Effect sizes are partial eta-squared values. Effect sizes of greater than 0.5 are indicated in bold.

(a) Velocity	t1	t2	t3	t4	t5	t6
$F_{2,18}$	2.96	1.84	4.48	5.94	5.13	5.56
P	0.077	0.188	0.026	0.010	0.017	0.013
(Effect size)	(0.248)	(0.170)	(0.332)	(0.398)	(0.363)	(0.382)
Sound vs MistNet, P	N/A	N/A	0.019	0.013	0.085	0.135
(Effect size)			(0.477)	**(0.513)**	(0.295)	(0.231)
MistNet vs MistNet+Sound, P	N/A	N/A	0.302	0.105	0.022	0.009
(Effect size)			(0.118)	(0.266)	(0.461)	**(0.548)**
(b) Body angle of attack	t1	t2	t3	t4	t5	t6
$F_{2,18}$	1.94	1.96	1.52	2.56	7.49	11.63
P	0.173	0.169	0.246	0.105	0.004	0.0006
(Effect size)	(0.177)	(0.179)	(0.144)	(0.222)	(0.454)	**(0.564)**
Sound vs MistNet, P	N/A	N/A	N/A	N/A	0.156	0.359
(Effect size)					(0.211)	(0.094)
MistNet vs MistNet+Sound, P	N/A	N/A	N/A	N/A	0.011	0.001
(Effect size)					**(0.527)**	**(0.694)**
(c) Tail angle of attack	t1	t2	t3	t4	t5	t6
$F_{2,18}$	3.08	1.78	1.80	5.86	16.08	22.92
P	0.071	0.197	0.194	0.011	0.0001	0.00001
(Effect size)	(0.255)	(0.165)	(0.167)	(0.394)	**(0.641)**	**(0.718)**

Sound vs MistNet, *P*	N/A	N/A	N/A	0.059	0.005	0.015
(Effect size)				(0.341)	**(0.587)**	**(0.501)**
MistNet vs MistNet+Sound, *P*	N/A	N/A	N/A	0.030	0.003	0.0003
(Effect size)				(0.424)	**(0.653)**	**(0.783)**