



## SYMPOSIUM

### Using a Sound Field to Reduce the Risks of Bird-Strike: An Experimental Approach

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**Synopsis** Each year, billions of birds collide with large human-made structures, such as buildings, towers, and turbines, causing substantial mortality. Such bird-strike, which is projected to increase, poses risks to populations of birds and causes significant economic costs to many industries. Mitigation technologies have been deployed in an attempt to reduce bird-strike, but have been met with limited success. One reason for bird-strike may be that birds fail to pay adequate attention to the space directly in front of them when in level, cruising flight. A warning signal projected in front of a potential strike surface might attract visual attention and reduce the risks of collision. We tested this idea in captive zebra finches (*Taeniopygia guttata*) that were trained to fly down a long corridor and through an open wooden frame. Once birds were trained, they each experienced three treatments at unpredictable times and in a randomized order: a loud sound field projected immediately in front of the open wooden frame; a mist net (i.e., a benign strike surface) placed inside the wooden frame; and both the loud sound and the mist net. We found that birds slowed their flight approximately 20% more when the sound field was projected in front of the mist net compared with when the mist net was presented alone. This reduction in velocity would equate to a substantial reduction in the force of any collision. In addition to slowing down, birds increased the angle of attack of their body and tail, potentially allowing for more maneuverable flight. Concomitantly, the only cases where birds avoided the mist net occurred in the sound-augmented treatment. Interestingly, the sound field by itself did not demonstrably alter flight. Although our study was conducted in a limited setting, the alterations of flight associated with our sound field has implications for reducing bird-strike in nature and we encourage researchers to test our ideas in field trials.

#### Introduction

Millions, perhaps billions, of birds die each year from collisions with large human-made structures, such as buildings, communication towers, and wind turbines (Klem 1990; Longcore et al. 2012, 2013; Loss et al. 2013, 2014). Though likely under-reported (Longcore et al. 2008; Shaw et al. 2010), it is believed that such bird-strike is the largest source of accidental bird mortalities worldwide (Klem 2010) and is predicted to increase due to projected development activities of human populations (Drewitt and Langston 2008). While it is hard to assess how these large-scale fatalities influence populations of birds in the long term (Arnold et al. 2011;

Longcore et al. 2013), it is clear that species of conservation concern are currently threatened by increasing risks of bird-strike (Drewitt and Langston 2006; Longcore et al. 2013; Pagel et al. 2013; Loss et al. 2014).

Not only does bird-strike kill large numbers of birds, it also causes significant financial costs for multiple industries (e.g. wind energy, construction, communications, aerospace, and power industries) (Allan 2000). Bird-strike also impacts permitting and construction in some industries, which is a financial burden, causes delays, and can result in a loss of potential development sites (Snyder and Kaiser 2009). Hence, it is clear that bird-strike is costly to

both wildlife conservation and to human economic development.

Not surprisingly, there has been substantial investment of resources in trying to reduce bird-strike. Most potential solutions rely on making human-made objects more visible to birds (Barrientos et al. 2012; Klem and Saenger 2013; Rössler et al. 2015) and some of these, especially treatments applied to windows, have been met with some success. However, it is clear that birds are still flying into human-constructed objects at increasing rates (Longcore et al. 2012, 2013; Loss et al. 2014). Why is that? One hypothesis is that many species of bird do not pay sufficient visual attention to what is directly in front of them as they fly during level-flight (Martin and Shaw 2010). For example, many species of bird have limited frontal binocular vision, because their eyes are placed rather laterally in their skulls (Martin 2011), resulting in poor spatial resolution of objects directly in front of the flight path. In addition, when the body and head are aligned to reduce parasite drag during level-flight, it is likely that the direction of visual gaze is directed down toward the ground. After all, birds have evolved to use landmarks on the ground for navigation purposes and the intrusion of large structures sometimes >100 m above the ground is an evolutionarily recent occurrence. By modeling the world through the sensory systems of birds, we might be able to design better mitigative technologies that reduce bird-strike and other conflicts caused by human development of the landscape (Martin 2011; Madliger 2012).

Here, we build on the hypothesis that bird-strike is associated with a relative lack of attention to the flight path directly in front of a flying bird and upon observations that birds might be less likely to collide with an object that they can see and hear (Dooling 2002). Specifically, it has been suggested that a “warning sound” ahead of a visible object may reduce the likelihood of bird-strike (Martin 2011). We test this proposal in this study.

Our goal was to investigate whether an obviously audible sound projected in front of a potential strike surface altered the flight of birds to reduce the risks and damage of bird-strike. To address this goal we trained captive zebra finches (*Taeniopygia guttata*) to fly down a flight corridor and through an empty wooden frame. Once birds were trained, we introduced three experimental treatments at unpredictable times between continuous training flights: (1) a loud sound field in front of the empty wooden frame; (2) a mist net in the wooden frame (i.e., a benign strike surface) but no sound field; and (3) both the loud sound field and the mist net. Using high-speed

digital videography, we quantified flight velocity and flight posture of birds. We hypothesized that the addition of the sound field in front of the mist net would alter flight behavior. Specifically, we predicted that birds would fly more slowly and increase the angle of attack of their bodies and tail, resulting in a more vertical (compared with horizontal) flight posture that would allow for slower flight.

## Methods

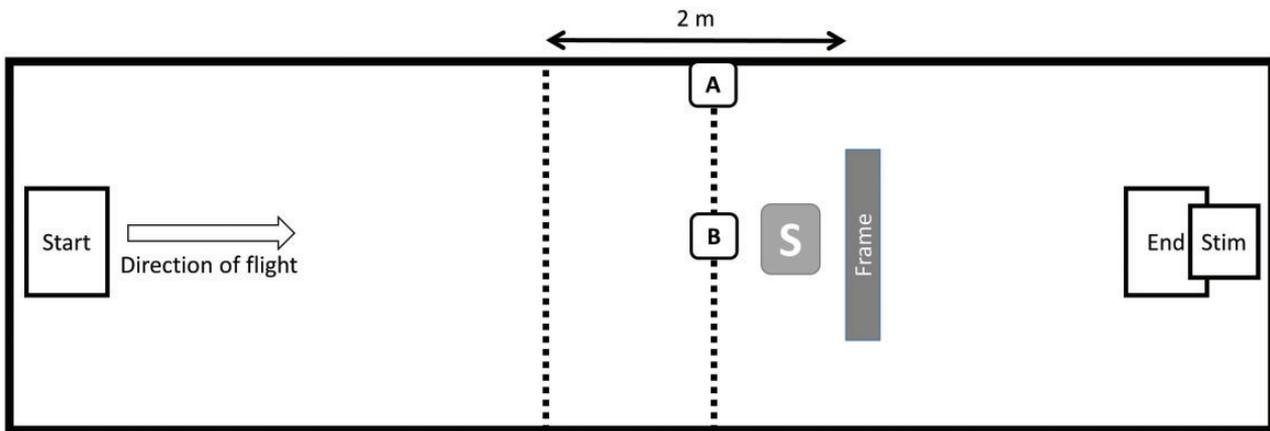
### Subjects and housing

We quantified flight behavior of 18 adult domestic zebra finches (8 males, 10 females), which we designated as experimental birds. These birds were housed in an indoor environmentally-controlled free-flight room (approximately  $3 \times 3 \times 2$  m) on a 14:10 L:D photoperiod with *ad libitum* access to food, grit, and drinking and bathing water. The room contained two open-sided cardboard boxes (approximately  $0.4 \times 0.25 \times 0.25$  m) that contained their perches, food, and grit. Both boxes were adorned with orange flagging tape to make them visually conspicuous and were positioned 0.9 m from the ground in the diagonally-opposite corners of the room to encourage flight between the open-sided boxes. Birds had to visit these boxes many times each day to feed and to roost. We placed a small housing cage (approximately  $0.25 \times 0.2 \times 0.4$  m) directly behind one of the open-sided cardboard boxes so that it was visible to birds in the box. We placed the open-sided boxes and the small housing cage in the birds’ free-flight room as identical boxes and cage were used in the experimental flight corridor (see below) and the birds’ pre-exposure to these objects assisted with flight training.

We housed three additional adult domestic zebra finches (1 male, 2 females) in a wire cage (approximately  $0.6 \times 0.4 \times 0.4$  m) in the same general environmental conditions as the experimental birds, but in a separate room. These birds were designated as “stimulus” birds and used as an attractant for the experimental birds during flight trials.

### Flight corridor

Our experimental arena was an outdoor, wire-mesh flight corridor (approximately  $8.5 \times 2.5 \times 2.2$  m, Fig. 1) that had a translucent, corrugated plastic roof. We lined most walls with thin plastic sheeting to control lighting and to insulate the corridor when flights were performed during colder weather. We placed a floor-to-ceiling open wooden frame (1 m wide, 2.2 m tall) at 6 m along the corridor. In some experimental trials (see below) a mist net was placed



**Fig. 1** A plan view of the flight corridor. “Start” indicates open-sided start box; “End” indicates open-sided end box; “Stim” indicates the three stimulus birds in a wire cage; “Frame” denotes position of open wooden frame; “S” in box indicates the location of the directional speaker, which faced directly upward; “A” and “B” indicate the positions of the two GoPro cameras.

within this frame, otherwise it was open so that birds were trained to fly through it. A highly directional speaker (Holosonics Audio Spotlight 168i) was placed flat on the corridor floor 0.5 m in front of the wooden frame and facing directly upward such that when a sound was played through the speaker we created a column of noise directly in front of the frame. To minimize the scattering of sound waves from the speaker we affixed sound-absorbing foam (Sound Proof Cow, item # 997161) to the walls, floor, and ceiling in this area (Fig. 1). We confirmed that the speaker and foam arrangement produced a reasonably discrete column of sound directly in front of the wooden frame by collecting sound pressure level (dBA) readings with a handheld meter (refer to ‘Sound mapping’ section below).

We placed an orange-flagged, open-sided cardboard box, identical to those in the housing room, at both ends of the flight corridor. We designated the box furthest from the wooden frame as the “start box” and this was where all birds were released from. The box at the opposite end of the corridor was the “end box.” We placed the three stimulus birds in a small wire cage (approximately  $0.25 \times 0.2 \times 0.4$  m) directly behind the open-sided end box so that they were visible to birds flying down the corridor (Fig. 1). In order to help gauge distances from the wooden frame, we marked the floor, ceiling, and wall of the flight corridor with high-contrast taped lines that demarked distances of 1 and 2 m in front of the wooden frame.

To record birds’ flight we used two GoPro Hero4 Black high-speed digital video cameras, recording at 120 frames per second. One camera was placed perpendicular to the length of the flight corridor (camera A, Fig. 1). The other (camera B) was affixed to

the ceiling and recorded directly downward (except for the first five trials where it was mounted on the floor and pointed up) and was aligned in the same axis as the length of the corridor. We carefully aligned both cameras so they could be combined to estimate three-dimensional movements of the birds in flight. We also calibrated each camera before every bout of flight trials with standardized grid images (with  $0.1 \times 0.1$  m cells) so that we could assess birds’ flight in all three planes of movement. Though the cameras were not explicitly synchronized, we used the occasions when birds crossed the 1 and 2 m markings on the corridor’s walls and floor to help synchronize frames of videos from the two cameras for a single flight trial. We recognize that this methodology introduces some random noise to our flight reconstructions but it does not bias our data toward supporting particular hypotheses.

### Sound mapping

Before commencing flight trials, we confirmed that the speaker produced the intended sound field. We used a handheld sound pressure level meter (Extech 407730, using A-weighting) to record sound pressure at points that were 0.4 m apart in a three-dimensional grid, starting at the floor of the corridor and moving in all directions to sample the entire space that birds could fly through. This procedure ensured that there was a column of noise at  $\sim 82$  dBA SPL directly above the speaker and that the noise fell away to close to background levels within 1 m in all directions. Hence, as birds flew toward the wooden frame they experienced a loud sound field starting  $\sim 1$ – $1.5$  m in front of the frame and this sound field persisted slightly through the frame.

### Flight training

From April to August 2015 and from December 2015 to February 2016 experimental birds experienced flight training in the experimental corridor. A flight training trial began when an experimenter released a pair of birds from the start box with the simultaneous sounding of a startle stimulus (sports whistle). The goal of the training was for birds to fly directly from the start box to the end box and pass through the wooden frame. For the following 120 min of the trial, the experimenter walked the length of the corridor, encouraging both birds to fly directly between the start and end boxes, through the wooden frame, in both directions up and down the corridor. When a bird made a complete flight from one end of the aviary to the other, the birds was given 3–5 min rest so that they did not become overtly fatigued.

During these initial bidirectional training trials, we recorded whether each bird flew through the wooden frame. Once a bird flew from one box to the other and directly through the wooden frame in >65% of all flights within a bidirectional learning trial, it progressed to the next series of learning trials (unidirectional). We often paired slower learners with a tutor bird who had already learned the flight task. This appeared to accelerate learning. On average, each bird made 12.8 (SE=1.0) complete flights from one box to the other during a bidirectional flight-learning trial. Birds experienced an average of 8.9 (SE=1.07) bidirectional flight-training trials before passing the learning criterion.

Once a bird succeeded at the bidirectional trials, it individually (i.e., without a partner) experienced unidirectional flight-training trials. The goal of these trials was to ensure that a single bird could be released (from inside a standardized cardboard tube, 8 cm diameter) from the start box and fly directly to the end box, through the wooden frame (Fig. 1). Upon release an experimenter sounded the startle stimulus, as before. Following a single flight, the experimental bird was caught with a hand-net before being released for a further training flight. We recorded whether or not each bird flew through the wooden frame during these trials. All experimental birds experienced one unidirectional training trial, which comprised an average of 3.7 separate flights (SE=0.3). Once a bird flew through the center of the empty wooden frame on three consecutive (or three out of four) unidirectional flights, it was considered to have passed unidirectional flight training and progressed to the experimental flight trials.

### Experimental flight trials

To start an experimental flight trial, each bird individually experienced a maximum of six unidirectional flights (as described above). Once a bird flew through the wooden frame in three consecutive flights (out of six possible), it then experienced a further one to four (randomly determined) unidirectional flights immediately followed by an experimental treatment. If it did not reach the initial criterion (i.e., three consecutive flights through the wooden frame), the bird returned to unidirectional flight training. This sequence of unidirectional flights allowed us to ensure that the bird was still flying from the start to the end box through the wooden frame, and then was also presented with an experimental treatment on an unpredictable occasion.

There were three experimental treatments: (1) *Sound*, where the speaker in front of the empty wooden frame emitted a 2–10 kHz sound at ~82 dBA SPL at 1 m above the speaker; (2) *MistNet*, where the speaker was turned off and a soft but taut mist net was placed inside the wooden frame to act as a benign strike surface; and (3) *Both*, where both the speaker was turned on and the mist net was placed in the frame. A bird could experience one treatment only for each day's experimental flight trial. The ordering of presentation of treatments was balanced so that across the 18 subjects there was no order bias for any experimental treatment.

Immediately following an experimental treatment flight, each bird experienced a maximum of six further unidirectional flights or until the bird flew through the wooden frame on three consecutive flights, whichever occurred first. This procedure helped to reinforce that birds needed to fly from the start to the end box and through the wooden frame. Birds experienced all of their flights within a trial in sequence without interruption. Each bird had at least 1 day off from any flight trials following an experimental trial.

### Flight video analysis

We extracted videos from the cameras (GoPro Hero4 Black, recording at 120 frames per second) using GoPro Studio software for Windows and exported files in .AVI format. We analyzed flight videos for all experimental flights and for the unidirectional flight that immediately preceded each experimental trial. This unidirectional flight served as a reference flight that accounted for variation in individual flight behavior that was not explained by treatment effects. For each video, we extracted single frames using Virtual Dub software as high-resolution JPG files. We started frame extraction when the bird first

reached the line on the aviary floor/wall that was 2 m in front of the wooden frame (Fig. 1), and extracted the preceding 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 (National Institutes for Health). In ImageJ, we calibrated each day's frames to the measured distances recorded on the calibration grids—which were placed at distances from the camera that were typical of where birds flew in the corridor. This procedure allowed us to generate coordinates in horizontal ( $x$ ) and vertical ( $y$ ) planes from the camera that recorded from the side (camera A) and from lateral ( $z$ ) plane from the camera that recorded from the ceiling (or the floor) (camera B). The two cameras were approximately synchronized as the first frame was always when the bird crossed the 2 m line. We accept that this is not a perfect synchronization procedure and it would introduce some random error; however, we cannot see any reason why this error would be different across treatment groups and so not bias us toward any of our hypotheses. In reality, almost all birds moved very little in the  $z$ -plane and analysis of two-dimensional movements (just  $x$  and  $y$ ) rendered qualitatively similar results as to what we present here.

For each bird's side-on video (camera A) we digitized the following points on the body to generate  $x$ - and  $y$ -plane coordinates: the distal tip of the bill (*bill*), the middle point of a line that bisected the body in a dorsal-ventral direction immediately behind the wing (*body*), and the distal tip of the center of the tail (*tail*). For each ceiling/floor video (camera B) we digitized the distal tip of the bill (*bill*) only to generate a  $z$ -plane coordinate. These coordinates allowed us to measure flight velocity (using the time sequence of *bill* coordinates), angle of attack of the body (angle from the horizontal of a straight line between *bill* and *body* coordinates within a frame on camera A), and angle of attack of the tail (angle from the horizontal of a straight line between *body* and *tail* coordinates within a frame on camera A). We averaged velocity and angle measurements for every group of five frames (i.e., t1 = frames 1–5, t2 = frames 6–10, t3 = frames 11–15, t4 = frames 16–20, t5 = frames 21–25, t6 = frames 26–30) to help minimize digitization error yet to still give a time sequence of flight metrics for each video. All videos were digitized and analyzed blind to treatment group.

### Statistical analyses

We calculated three change variables (for velocity, body angle, and tail angle) by subtracting

performance in the reference flight (the unidirectional flight immediately preceding an experimental treatment flight) from performance in each treatment flight (*Sound*, *MistNet*, *Both*), for each bird. A negative value in the velocity-change statistic meant a bird flew slower in the treatment relative to the most recent reference flight. A positive value in any angle of attack change statistic indicated a larger angle of attack in the treatment flights relative to the reference flight.

We used a repeated-measure ANOVA to test our hypotheses, by comparing the differences in the change variables (velocity, body angle, tail angle, in separate models) among treatments within each bird, across all time periods (t1 through t6). Treatment group (*Sound*, *MistNet*, *Both*) and time period (1–6) were both treated as within-subject fixed factors. We also inspected two *a priori* contrasts: *Sound* versus *MistNet*, which helped us to interpret whether the presence of a sound field elicited a similar response as to the presence of a barrier (i.e., mist net); and *MistNet* versus *Both*, which helped us understand whether the addition of a sound field in front of a strike surface altered flight behavior further. We interpreted effect sizes (partial eta-squared) of these tests along with visual inspection of estimated marginal means and associated confidence intervals. All analyses were performed with IBM SPSS Statistics v23 employing two-tailed tests of probability.

### Results

Two birds were removed from the analyses as they deviated sufficiently from a central flight path during their *Both* experimental flight such that we could not adequately digitize their movements. Although anecdotal, these birds avoided the mist net completely and were the only birds to do so in the study, and they did this in their *Both* treatment only.

Within-individual change in flight velocity (relative to the most recent reference flight for each bird) differed by experimental treatment group ( $F_{2,30} = 10.16$ ,  $P < 0.0005$ , effect size = 0.404) and over the time sequence as birds approached the wooden frame ( $F_{5,75} = 11.84$ ,  $P < 0.0001$ , effect size = 0.441). In addition, there was a treatment-by-time interaction, indicating that the pattern of how velocity changed over time was different among the treatment groups ( $F_{10,150} = 2.75$ ,  $P = 0.004$ , effect size = 0.155). Inspection of *a priori* contrast indicated that the *Sound* treatment differed from the *MistNet* treatment ( $F_{1,15} = 8.17$ ,  $P = 0.012$ , effect size = 0.353) and the *Both* treatment differed from the *MistNet* treatment ( $F_{1,15} = 12.53$ ,  $P = 0.003$ , effect size = 0.455). By visual inspection of estimated

marginal means and associated confidence intervals, we could see that the *Sound* treatment generally had little effect on flight velocity, whereas velocity decreased in the *MistNet* and *Both* treatments as birds approached the wooden frame (Fig. 2). In addition, the *Both* treatment resulted in a much larger (approximately twice as much) deceleration of flight than did the *MistNet* treatment. 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 notably reduces flight velocity close to the time of contact with the barrier (i.e., at t6).

The experimental treatments had a notable effect on body angle of attack ( $F_{2,30} = 16.71$ ,  $P < 0.00002$ , effect size = 0.527) and an even larger effect on tail angle of attack ( $F_{2,30} = 24.72$ ,  $P < 0.00001$ , effect size = 0.622). Both body and tail angles changed during the flights, getting larger as the birds approached the wooden frame (body angle,  $F_{5,75} = 12.65$ ,  $P < 0.00001$ , effect size = 0.458; tail angle,  $F_{5,75} = 16.36$ ,  $P < 0.00001$ , effect size = 0.522; Fig. 2). As with the velocity analysis, there was a notable treatment-by-time interaction effect, indicating that the way in which body and tail angles changed over time was different among the treatment groups (body angle,  $F_{10,150} = 6.00$ ,  $P < 0.00001$ , effect size = 0.286; tail angle,  $F_{10,150} = 7.81$ ,  $P < 0.00001$ , effect size = 0.342; Fig. 2).

The *a priori* contrasts indicated that body angle differed somewhat between *Sound* and *MistNet* treatments ( $F_{1,15} = 7.09$ ,  $P = 0.018$ , effect size = 0.321) and differed substantially between *MistNet* and *Both* treatment groups ( $F_{1,15} = 25.86$ ,  $P = 0.0001$ , effect size = 0.633). By examining the confidence intervals around these patterns (Fig. 2), we can see that birds did not substantially alter their body angle of attack in the presence of the mist net alone or with the sound field alone. However, if a sound field was in front of the mist net then birds made large changes to their body posture, increasing their angle of attack to be more vertical as they approached the wooden frame (Fig. 2).

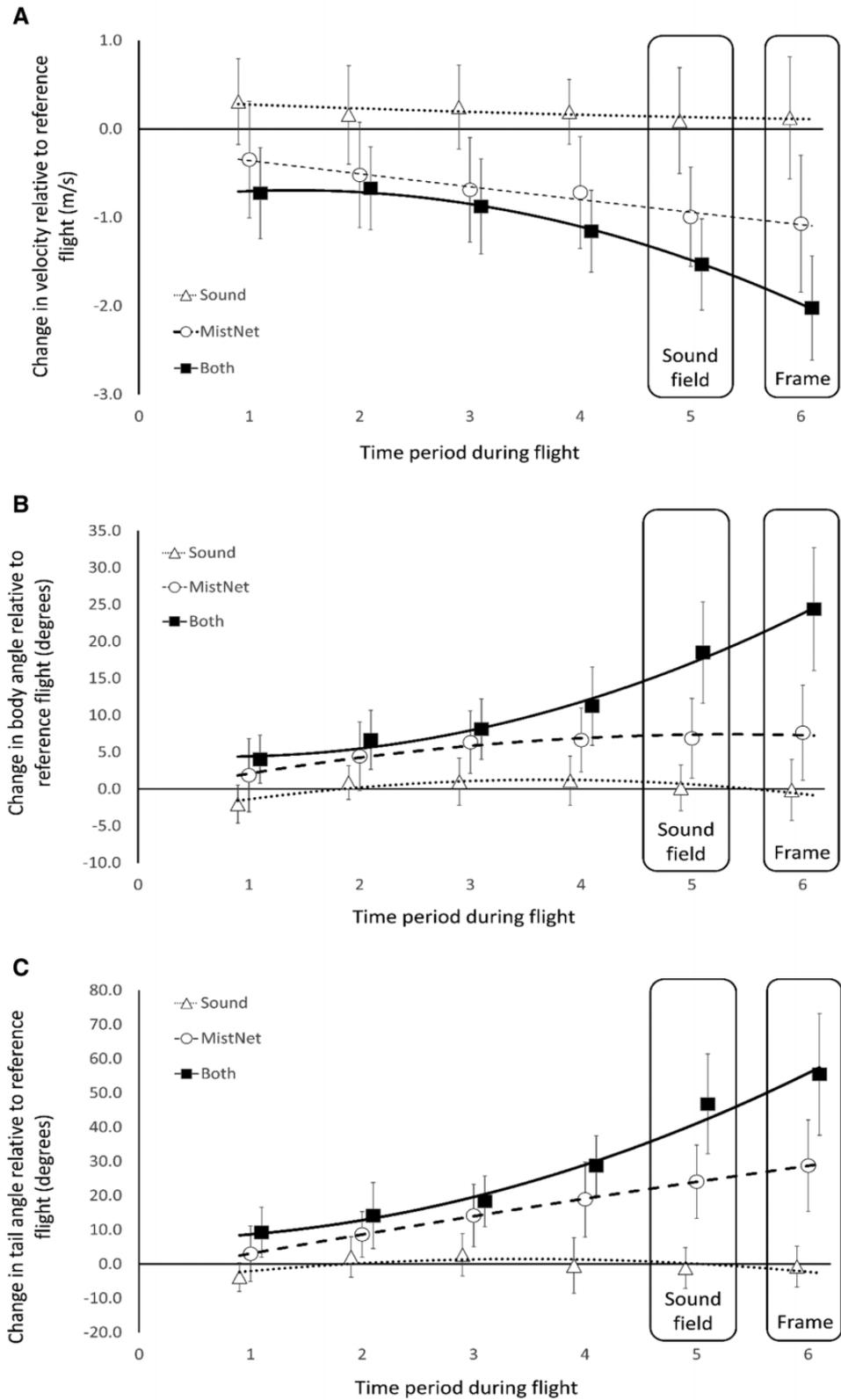
There were stronger differences in tail angle of attack among treatment groups. The *MistNet* treatment elicited a larger tail angle of attack than the *Sound* treatment ( $F_{1,15} = 19.38$ ,  $P = 0.001$ , effect size = 0.564; Fig. 2). In addition, the *Both* treatment elicited an even larger increase in tail angle of attack than the *MistNet* treatment ( $F_{1,15} = 28.42$ ,  $P = 0.00008$ , effect size = 0.654; Fig. 2). These data are consistent with the flight velocity analyses in that the increased angle of attack of the tail, lowering of the distal tip of the tail relative to the body, was associated with slower flight velocity.

## Discussion

Our results indicate that in the presence of a visible strike surface, an intensely audible sound field caused birds to slow down their flight and alter their body and tail position away from a horizontal flight posture (Fig. 2). Specifically, birds reduced their flight velocity by approximately twice as much when the sound field was placed in front of a mist net, compared with their flight velocity when the sound field was not present. On average, birds flew at 4.82 m/s (SE = 0.24) during reference flights, and slowed this by 2.02 m/s on average when exposed to the sound field in front of the mist net (*Both* treatment). When the mist net was present without the sound field (*MistNet* treatment), birds typically reduced their flight velocity by 1.07 m/s. This difference of 0.95 m/s between the treatments is an approximate 20% reduction in flight velocity relative to typical reference flights, indicating a potential benefit to placing a sound field in front of a strike surface. A 20% reduction in flight velocity would result in the bird colliding with an object with much lower force (energy that would be dissipated at collision is proportional to velocity-squared) and/or increasing the possibility of the bird avoiding the object altogether. Of note, birds in our experiment flew fairly slowly relative to free-living birds in cruising and/or migratory flight. This is expected as our study was conducted in a spatially-limited aviary setting where birds cannot fly as quickly as in the wild. However, if the relative reduction in flight velocity that we quantified here (~20%) translates to similar relative reductions in free-living birds, who might be flying at 10–15 m/s, the decrease in the force of collisions could be substantial. We encourage further testing of our technology on faster-flying birds over a large spatial scale so that we can better quantify likely reductions in the probability and/or force of collisions.

Slower flight speeds might also allow birds to more appropriately assess the distance to manmade obstacles in their environment (Martin 2007, 2011). More rapid movement of the bird would increase optic flow on the retina (Land 1999), which would likely make it more difficult for that individual to perceive relative distances accurately. Hence, by flying more slowly birds would not only have more time to make evasive maneuvers but also likely have a more accurate perception of where objects are in their environment (Lin et al. 2014; Williams and Biewener 2015), thereby reducing the risks of bird-strike.

In association with this notable decrease in flight velocity the birds increased the angle of attack of their bodies and tails, lowering the end of the tail



**Fig. 2** Within-individual change, relative to the most recent reference flight, in flight parameters during the six time periods of each flight (1–6). Graphs show estimated marginal means ( $\pm$  95% confidence intervals) for (A) velocity, (B) body angle of attack, and (C) tail angle of attack. Lines on the graphs are fitted polynomials within each treatment group. The sound field was experienced most intensely at time period 5 and the wooden frame was experienced at time period 6, as indicated by the highlighted areas on the graphs.

to a more vertical position as the bird approached the wooden frame that held the mist net. This increase in tail angle of attack permits slower flight without aerodynamic stall (Norberg 1990) and also influences drag to directly affect flight velocity (Thomas 1993, 1996). The types of flight posture changes we observed when the sound field was combined with the mist net (*Both* treatment) was similar to the changes that birds make as they prepare for landing—decreasing velocity and lifting the head and body relative to the tail (Berg and Biewener 2010). The increased angle of attack of the body may allow birds to redirect aerodynamic forces and shift between flight modes (Berg and Biewener 2010). Specifically, we propose the increased body angle permits greater maneuverability and thereby could decrease the likelihood of collision (Bevanger 1994; Janss 2000; Drewitt and Langston 2008). In addition, the alteration of flight posture we observed in response to the *Both* treatment could reduce the likelihood of a fatal collision when bird-strike occurs, as birds in a more vertical posture could absorb the impact with their feet, bodies, and wings rather than the head alone, which would occur if the bird was flying more horizontally. Many bird-strikes in nature result in fatalities due to head injuries (Klem 1990; Veltri and Klem 2005).

We propose that we observed these alterations of flight behavior because the sound field is attracting the visual attention of the birds—it is an unusual and highly conspicuous sound that they have rarely (if ever) heard before—resulting in the birds noticing the mist net either sooner or more effectively than when the sound field is not present. Although we did not measure the direction of gaze directly, the increased body and tail angles of attack would likely bring the head up and direct the birds' line of sight into a more forward pointing direction. This change in the direction of vision is supposition on our part, but it would be interesting to assess direction of gaze in further tests. Another line of evidence that is consistent with our interpretation is that the sound field by itself (*Sound* treatment) did not lead to consistent alterations of flight. This observation implies that the sound alone does not actively deter the birds. If the sound drew visual attention then birds in the *Sound* treatment would see an empty wooden frame and continue their flight as in the reference flights—which is the pattern we observed.

For field applications, we propose to project the sound much further in front of the strike surface than in this study. Because of space and logistic constraints the sound field in our experiment was only 1–1.5 m in front of the mist net. This did not allow

for the extent of response that could be possible if the sound was projected tens of meters in front of the surface. For example, to reduce building or wind turbine strike, we recommend that speaker be mounted on, or close to, the structure and projected in the direction from which the birds usually fly and be audible more than 30 m from the strike surface. This may increase the likelihood that birds can avoid collision altogether. While we are not aware of any field tests of this kind, it would seem a logical next step given the strength of the results we obtained in a more limited setting. Consistent with our interpretations of our study and the potential applications of our sound fields, Dooling (2002) has hypothesized that wind turbines that emit high-frequency noises, in addition to the usual sounds of the turbines, will make the turbines more noticeable to flying birds and perhaps reduce the probability of bird-strike.

If the sound field works to attract visual attention we suggest that such sounds are deployed in combination with window treatments and visual deterrents (Klem 2009; Klem and Saenger 2013; Rössler et al. 2015). We predict that the sound field could enhance the functioning of visual deterrents. However, birds also appear to fly into structures because some visual cues are active attractants—for example, red navigation lights affixed to communication towers and office lights at night in high-rise buildings (Gauthreaux and Belser 2006; Longcore et al. 2013; Gehring et al. 2015). At this point, we do not recommend the deployment of our sound fields in such situations, as increased visual attention may accentuate the attractiveness problems of these particular cues.

In addition to progressing to field trials, we also suggest that researchers examine the responses of flocks of birds to similar acoustic warning devices. In nature, bird-strike often occurs with flocks of birds and responses of a group may be different than responses of single individuals.

In conclusion, we show that a loud, conspicuous sound field projected in front of a strike surface results in substantially slowing of flight velocity and an alteration of flight posture that would likely reduce collision-induced damage to birds and allow for more maneuverability. We propose that the sound field operates to attract the visual attention of a flying bird—a form of “acoustic lighthouse”—giving the bird more time to adjust its flight and minimize the risks of bird-strike. The next step will be to project similar sound fields in front of buildings, turbines, communication towers, and other large structures to examine whether we can reduce actual bird-strike in nature.

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