Ultraviolet-reflective film applied to windows reduces the likelihood of collisions for two species of songbird

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Perhaps a billion birds die annually from colliding with residential and commercial windows. Therefore, there is a societal need to develop technologies that reduce window collisions by birds. Many current window films that are applied to the external surface of windows have human-visible patterns that are not aesthetically preferable. BirdShades have developed a short wavelength (ultraviolet) reflective film that appears as a slight tint to the human eye but should be highly visible to many bird species see in this spectral range. We performed flight tunnel tests of whether the BirdShades external window film reduced the likelihood that two species of song bird (zebra finch, *Taeniopygia guttata* and brown-headed cowbird, *Molothrus ater*) collide with windows during daylight. We paid particular attention to simulate the lighting conditions that birds will experience while flying during the day. Our results indicate a 75-90% reduction in the likelihood of collision with BirdShades-treated compared with control windows, in forced choice trials. In more ecologically relevant comparison between trials where all windows were either treated or control windows, the estimated reduction in probability of collision was 30-50%. Further, both bird species slow their flight by approximately 25% when approaching windows treated with the BirdShades film, thereby reducing the force of collisions if they were to happen. Therefore, we conclude that the BirdShades external window film will be effective in reducing the risk of and damage caused to populations and property by birds' collision with windows. As this ultraviolet-reflective film has no human-visible patterning to it, the product might be an aesthetically more acceptable low cost solution to reducing bird-window collisions. Further, we call for testing of other mitigation technologies in lighting and ecological conditions that are more similar to what birds experience in real human-built environments and make suggestions for testing standards to assess collision-reducing technologies.

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Abstract

16 Perhaps a billion birds die annually from colliding with residential and commercial
17 windows. Therefore, there is a societal need to develop technologies that reduce window
18 collisions by birds. Many current window films that are applied to the external surface of
19 windows have human-visible patterns that are not aesthetically preferable. BirdShades
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24 brown-headed cowbird, *Molothrus ater*) collide with windows during daylight. We paid
25 particular attention to simulate the lighting conditions that birds will experience while
26 flying during the day. Our results indicate a 75-90% reduction in the likelihood of collision
27 with BirdShades-treated compared with control windows, in forced choice trials. In more
28 ecologically relevant comparison between trials where all windows were either treated or
29 control windows, the estimated reduction in probability of collision was 30-50%. Further,
30 both bird species slow their flight by approximately 25% when approaching windows
31 treated with the BirdShades film, thereby reducing the force of collisions if they were to
32 happen. Therefore, we conclude that the BirdShades external window film will be effective
33 in reducing the risk of and damage caused to populations and property by birds' collision
34 with windows. As this ultraviolet-reflective film has no human-visible patterning to it, the
35 product might be an aesthetically more acceptable low cost solution to reducing bird-
36 window collisions. Further, we call for testing of other mitigation technologies in lighting
37 and ecological conditions that are more similar to what birds experience in real human-
38 built environments and make suggestions for testing standards to assess collision-reducing
39 technologies.
40

Introduction

42 More than a billion birds die annually in night- and daytime collisions with residential and
43 commercial windows (Klem, 2014; Loss et al., 2014; Loss, Will & Marra, 2015; Ocampo-

44 Peñuela et al., 2016; Schneider et al., 2018). It is likely that this pattern of mortality not
45 only creates conservation issues for some avian populations but also raises significant
46 political and socioeconomic barriers to human development of the landscape (Loss et al.,
47 2014; Klem, 2015). Therefore, there are pressing societal needs to develop technologies
48 that reduce window collisions by birds during daylight hours (Hager et al., 2013; Klem &
49 Saenger, 2013). Night-time collisions likely occur for other reasons, which we do no
50 address in this study.
51   It has been proposed that birds collide with windows as they perceive the window
52 as a reflective or transparent surfaces that extend their environment (Klem, 2009). In other
53 words, they do not perceive the window as a solid barrier that they cannot fly through.
54 Though this hypothesis is largely untested in the literature, several companies have
55 produced film treatments that can be applied to the external surface of windows to make
56 the glass more visible to birds despite its reflective properties. Numerous tests of
57 commonly available surface film applications claim that visible vertical stripes of particular
58 widths and separations, as well as some arrangements of dot and shape patterns that do
59 not leave too much open space on the windows, are effective in reducing collisions by birds
60 (Klem & Saenger, 2013; Rössler, Nemeth & Bruckner, 2015; Sheppard, 2019).
61   Despite the claims in the published literature, we are not aware of any flight tunnel
62 tests that employ lighting conditions that realistically simulate the lighting environments
63 that birds would experience during the day, which may influence the perception of
64 windows as reflective surfaces. A bird that might collide with a window during the daytime
65 will experience daylight on the external surface of the window and artificial light (e.g., at a
66 residential or commercial building) on the internal surface. These lighting conditions will
67 affect whether and how the bird perceives the window as a reflective surface. We expect
68 there would be greatest reflection when there is relatively more light on the external
69 compared with internal surface of a window. Most flight tests of window collisions appear
70 to have been conducted in highly darkened flight tunnels, that will lack important shorter-
71 wavelength light cues, and/or with mirror-reflected light that will alter the polarization of
72 light (Rössler, Nemeth & Bruckner, 2015; Sheppard, 2019). For those experimental field
73 tests that have used natural-occurring daylight on the external surface of windows (Klem,
74 2009; Klem & Saenger, 2013), we are not aware of any experiments that have
75 simultaneously used commonly-occurring artificial light on the internal surface of the
76 windows. Increased brightness of artificial lighting on the internal surface of a window
77 should reduce the perception of reflection. Hence, there is a need to test collision-reducing
78 technologies in daylight with appropriate artificial light placed behind the window.
79   In addition to considering the external and internal lighting conditions, there has
80 been debate about the relative merits of captive flight tunnel testing versus free-living field
81 testing of factors that influence window collisions (Klem & Saenger, 2013; Sheppard, 2019).
82 It may be that testing collision-reducing technology in free-living birds is desirable as birds
83 are likely in more naturalistic physiological and behavioral states in such tests. However,
84 field experiments lack as much experimental control as flight tunnel tests and observing
85 collisions in free-living birds is relatively rare and poses welfare and ethical issues as some
86 of these collisions lead to known damage to experimental subjects (Klem, 2009). Flight
87 tunnel tests are also appealing as data can be collected in a relatively short period of time
88 and conditions can be replicated more easily to form a more standardized protocol to guide
89 international efforts in assessing collision-reducing technologies. We attempted to take a

90   middle-ground in this debate by using both domesticated and wild-caught birds in
91   controlled flight tunnel tests, though we recognize it will be important to take steps to test
92   collision-reducing technologies with birds in free-living situations also. The domesticated
93   birds will experience less physiological and behavioral alteration due to handling yet
94   render ecologically-relevant data as their lineage was derived from a free-living species.
95   Specially, we conducted flight tunnel tests of a new collision reducing technology.
96   BirdShades has produced a window film that is reflective in the shorter-wavelength (e.g.
97   ultraviolet) bands of light and lacks a human-visible striping pattern. The lack of a striping
98   pattern might make the film more aesthetically acceptable than the striped films that are
99   currently often used in residential and commercial buildings. To many birds, including both
100   passerines (Hart, 2001) and non-passerines (Goldsmith & Butler, 2005; Lind et al., 2013), a
101   film that reflects shorter wavelengths of light should be visible as a solid surface. To the
102   experimenters' eyes, the BirdShades film had a very light blue tint but otherwise seemed
103   highly translucent. Here, we conducted controlled flight tunnel tests of the efficacy of the
104   BirdShades window treatment in realistic daylight collision conditions.
105   We performed flight-collision tests with two song bird species, zebra finch
106   (*Taeniopygia guttata*) and brown-headed cowbird (*Molothrus ater*), that are known to be
107   sensitive to shorter-wavelengths of light and hence be good candidate species to benefit
108   from the BirdShades window treatment (Hart, 2001; Aidala et al., 2012). Specifically, we
109   constructed a long flight tunnel in which the birds flew toward two windows in daylight.
110   Behind each window we placed suitable artificial lights. The windows were tilted back
111   slightly to reflect the sky and, potentially, give the birds the perception of flying into open
112   space. We flew all individuals in three conditions: (i) control, where windows were treated
113   with an external transparent film; (ii) treatment, where the windows were treated with the
114   BirdShades external film; and (iii) both, where one window received the control condition
115   and the other the BirdShades treatment. We placed a fine mist net in front of the windows
116   to prevent actual collisions. We video recorded all flights and analyzed those recordings for
117   the direction and velocity of each bird to assess the likelihood of collision in all
118   experimental conditions.
119

Materials & Methods

121   Experimental subjects and housing
122   We performed flight trials with two species of songbird (zebra finches N = 24, and brown-
123   headed cowbirds N = 18) in our custom-built flight tunnel in Williamsburg (Virginia, USA),
124   to test whether the BirdShades window treatment reduces the risk of collision with
125   windows. When not in the experimental flight tunnel, the zebra finches were housed in an
126   outdoor aviary (3 x 3 x 2.5 m) and fed ad libitum Volkman science seed mix and had access
127   to ad libitum drinking, bathing water, and perches. The zebra finches were selected,
128   somewhat arbitrarily but with the condition that the individuals appeared to fly well in
129   their large free-flight aviaries, from our larger stock colony that we have maintained for 19
130   years. The brown-headed cowbirds were caught in a baited walk-in trap at a local farm and
131   housed in a long outdoor flight aviary (10 x 3 x 2.5 m) with access to ad libitum food (50:50
132   blend of commercial chick crumbs with Volkman science seed mix), bathing water, and
133   drinking water. Cowbirds were in these captive conditions for approximately one week
134   before flight trials began to assure that all birds were healthy and flying well before the

135   experiment commenced. All zebra finches were banded with a metal leg banded that had a
136   unique identifying number, while all cowbirds were given unique combinations of color
137   bands to identify individuals.
138
139   Flight tunnel and window treatments
140   The flight tunnel consisted of a long darkened release tunnel (7 x 1.2 x 1.2 m) that opened
141   into a larger day-lit collision tunnel (7.5 x 2.5 x 2.5 m) constructed with fine netting, where
142   the windows were placed (Figure 1). Birds experienced natural daylight in the collision
143   tunnel and the external surface of the windows experienced natural daylight during all
144   trials (Figure 2). We conducted all trials between 0900 and 1230 from September to
145   December 2019. Around and behind each of the two framed windows, we constructed a
146   lighting box so that the internal surfaces of each window were illuminated with artificial
147   lighting that is representative of residential or commercial buildings. We used two
148   TaoTronics 12 W LED lamps on their highest brightness setting behind each window.
149   Hence all flight tests were conducted in realistic lighting conditions—natural daylight on
150   the external surface and artificial indoor lighting on the internal surface of the windows.
151   We placed the windows side-by-side with an opaque connector to give the
152   appearance of two windows in a solid wall. There was a 0.5 m gap on both the left and right
153   side of this wall of windows so that birds could divert their flight laterally as to avoid
154   collision. We placed a fine mist net 1 m in front of the windows so that the birds did not
155   actually collide with the windows.
156   Each bird was exposed to each of three treatment groups, in a balanced order so
157   that the series of presentations and repeated exposure to the flight tunnel did not bias
158   responses by birds. We chose a repeated-measures experimental design as this accounts
159   for among-bird variation in flight behavior that otherwise requires large sample sizes.
160   Birds experienced each treatment group on a separate day, to minimize changes in
161   behavior associated with repeated exposure to the flight tunnel and window. The three
162   treatment groups were as follow: (i) Control. We applied an external film to both windows
163   that had similar physical and spectral-reflectance properties to the BirdShades film except
164   for the reflectance in the ultraviolet wavelength range. This control film was provided by
165   the BirdShades organization. (ii) Treatment. We applied the BirdShades film product to the
166   external surface of both windows. (iii) Both. In these trials, one window received the
167   control film and the other received the BirdShades film, equally assigned to left and right
168   windows so there was no systematic side bias. This created a forced choice situation for the
169   birds.
170   Once applied, using instructions supplied by the manufacturer, all window coatings
171   were stored under heavy blankets to ensure that they remained in dark conditions when
172   not in use, so as not to degrade or damage the film coatings. We applied all of the films to
173   Pella 250 Vinyl glass double-glazed replacement windows, as a window commonly found
174   on residential and commercial buildings in the US. The experimental BirdShades film is
175   active in the near UVA range between 300-400 nm and is mostly transparent in the human-
176   visible range. Further information about the spectral reflectance and absorption of the
177   window film is available from BirdShades.
178   Before flight trials and at regular (approximately 30 min) intervals during each
179   session of trials, we measured ambient light irradiance immediately in front of the
180   windows using a handheld spectrometer (WaveGo, Ocean Insight). This periodic

181   assessment of ambient light allowed us to characterize the general daylight conditions in
182   which the birds experienced the window treatments. We also assessed the light spectra
183   emitted by the artificial lights by holding the spectrometer 0.5 m from the bulb of a single
184   illuminated lamp in an entirely darkened room, to eliminate other sources of light.
185
186   Flight trials and metrics of collision risk
187   Once the windows were placed in the frames, a flight trial commenced by releasing a single
188   bird from the hand approximately 2 m (from the opening) down the dark release corridor,
189   along with the experimenter emitting a loud startle sound. The bird (in most cases) flew
190   directly away from the experimenter and toward the windows in the open collision tunnel.
191   The windows were 5 m from the opening of the dark release corridor and the mist net was
192   4m from the end of the dark release corridor. Hence, for a bird to fly from the release point
193   to the mist net it had to fly for approximately 6 m.
194   We recorded all flight trials on two GoPro cameras (Hero7 Black at 30 frames per
195   second) so that we could recreate three-dimensional coordinates of birds in flight. In order
196   to maximize flight-path coverage, we used a wide angle (focal length: 15 mm) setting that
197   allowed for coverage of the entire volume of the day-lit collision tunnel. We synchronized
198   the cameras with both acoustic and visual cues. Lens distortion due to the wide-angle
199   modes was corrected for subsequent analysis, using the DWarp Argus package (Jackson et
200   al., 2016) implemented in Python 2.7. To recreate three-dimensional flight paths and flight
201   velocity of all birds, we calibrated the cameras and airspace using a wand-based, direct
202   linear transformation (DLT) technique with sparse-bundle adjustment (SBA), implemented
203   in the Argus package in Python 3.6.2 (Jackson et al., 2016). Specifically, we digitized the 3D
204   position of the centroid of each bird during the final 15 frames (0.5 s) of each flight and
205   calculated their average velocity across 5-frame intervals in this segment (i.e. frames 1-5,
206   6-10, 11-15 from the end of their flight). We used these three velocity measurements to
207   assess whether birds were altering their flight speed in response to the experimental
208   treatments.
209   We also visually examined all recorded flights to assess the probability of collision
210   with the windows. We determined that a collision was likely if the bird flew in line with the
211   windows and hit the mist net. If the bird flew too far to the right or left, as to miss the
212   windows, or stopped at least 1 m short of the mist net, we determined that the bird would
213   have avoided the window. We generated our measure of collision/avoidance for each bird
214   in each treatment group. Hence, for each flight of a bird in each treatment group our goal
215   was to produce an assessment of collision risk and a quantification of flight velocity.
216   However, not all birds flew successfully in all trials hence the actual sample sizes in
217   particular analyses were smaller than the total number of birds flown. We report actual
218   sample sizes in association with each statistical analysis.
219
220   Ethics statement
221   All procedures were approved by William & Mary's Institutional Animal Care and Use
222   Committee (2019-09-22-13861-jpswad). We caught brown-headed cowbirds under US
223   federal bird banding permit 21567 issued to Bryan Watts.
224
225   Statistical analyses

226 To test whether birds were more likely to 'collide' with control or treatment windows
227 when presented with 'both' in a forced choice trial, we employed a Wilcoxon matched-pairs
228 signed-ranks test where we scored collisions with a window (control or treatment) as 1
229 and avoidance as 0, and avoidance of both windows in a trial as 0.5. As this non-parametric
230 repeated-measures test analyzed rank data, the actual numerical values that we chose were
231 not that important. This approach enabled us to examine the within-individual preference
232 for colliding with (or avoiding) control versus treatment windows while not biasing the
233 outcomes with situations where a bird avoided both windows.
234   To examine the within-individual change in likelihood of window collision for birds
235 in the control compared to the treatment trials we used a Wilcoxon matched-pairs signed-
236 ranks test where we scored collisions with either window as 1 and avoidance of the
237 windows as 0. In this case, the matched-pairs were formed by the same bird experiencing
238 the two treatment conditions.
239   To test for changes in velocity of birds according to the sequence of the flight video
240 (i.e. frames 1-5, 6-10, 11-15) and the window treatments, we used a linear model in which
241 both time during the flight video and window treatment group were within-subjects fixed
242 factors.
243   We performed all analyses using IBM SPSS Statistics v25 employing two-tailed tests
244 of probability. All analyzed data are available in the linked dataset.

245

246 Results

247 Ambient irradiance and light spectra
248 Collation of collected irradiance spectra indicated that birds generally experienced the
249 windows in fairly bright daylight (mean ± SEM lux = 23824 ± 5278.2; Figure 2). It is
250 important to note that these spectral measurements are rich in shorter wavelength light,
251 which is typical of daylight conditions. The lamps we used also emitted a peak of shorter
252 wavelength light with another broad peak at intermediate to longer wavelengths of the
253 visible spectrum (lux = 422; Figure 2). From our scans of residential and office lighting in
254 our area, this spectrum and brightness is typical of the internal surface of many windows
255 (mean = 334, SD = 329, minimum = 12, maximum = 1847; all measurements in lux).

256

257 Zebra finches
258 Among the zebra finches, the birds were more likely to collide with a control window than
259 a treatment window when given the choice between the two in a forced choice (both) trial.
260 In 60% (N = 12 of 20) of these 'both' choice trials, birds were judged to 'collide' with one of
261 the windows. Of these 12 collision events, 8.3% (1 of 12) were with the BirdShades-treated
262 window and 91.7% (11 of 12) were with the control-treated window (Figure 3). These
263 differences could be interpreted as a 91% reduction in collision risk when windows are
264 treated with the BirdShades product compared with the control product (Wilcoxon Z =
265 2.63, N = 20 pairs, p = 0.0085; Figure 3).
266   However, although such tests are popular in the published literature and are useful
267 as a point of comparison to other published studies, these forced choice 'both' trials are not
268 realistic of how birds experience windows in nature. In real situations, all windows would
269 be treated in the same manner and it is more relevant to examine the differences in the

270   probability of collision when both windows are either experimentally-treated or control-
271   treated (i.e. likelihood of collision in control vs treatment trials, for each bird).
272   When both windows were control-treated, the zebra finches were less likely to
273   avoid the windows (15%, 3 of 20 trials) than to collide with the windows (85%, 17 of 20
274   trials) (left pair of bars on Figure 4). However, when the windows were both treated with
275   the BirdShades film, the zebra finches were marginally more likely to avoid the windows
276   (57.9%, 11 of 19 trials) than collide with the windows (42.1%, 8 of 19 trials) (right pair of
277   bars on Figure 4). Taken together, the zebra finches were approximately 50% less likely to
278   collide with a window if the windows were treated with the BirdShades film compared
279   with the control film (Wilcoxon, $Z = 3.29$, $N = 17$ pairs, $p = 0.001$; Figure 4).
280   Zebra finches adjusted their flight velocity according to the window treatments
281   ($F_{2,26} = 3.78$, $p = 0.036$) and decelerated as they approached the windows in all treatments
282   ($F_{2,26} = 90.46$, $p < 0.0001$; Figure 5). Specifically, the birds flew approximately 25% slower
283   when the windows were treated with the BirdShades film (planned contrast of control vs
284   treatment, $F_{1,13} = 11.20$, $p = 0.005$). The forced choice 'both' condition, where one window
285   was control-treated and the other was BirdShades-treated, rendered intermediate values
286   that were not different to the control trials (planned contrast of control vs both, $F_{1,13} =$
287   0.778, $p = 0.394$). As all groups decelerated at approximately equal rates, it appears that
288   birds adjusted their velocity early in their flight.
289
290   Brown-headed cowbirds
291   We observed qualitatively similar responses to the window treatments among the brown-
292   headed cowbirds as the zebra finches. The cowbirds were more likely to collide with a
293   control window than a BirdShades-treated window when given the choice between the two
294   in a forced choice trial (i.e. 'both' trials). In 88.2% ($N = 15$ of 17) of these forced choice
295   'both' trials, cowbirds were judged to likely collide with either window. Of these collision
296   events, 20% (3 of 15) were with the BirdShades-treated window and 80% (12 of 15) were
297   with the control-treated window (Wilcoxon, $Z = 2.02$, $N = 17$ pairs, $p = 0.043$; Figure 6).
298   This could be interpreted as a 75% reduction in the risk of collision.
299   When both windows were control-treated, the cowbirds all collided with the
300   windows (100% of 17 trials) with no avoidance (left bar on Figure 7). However, when both
301   windows in a trial were the BirdShades-treated windows, the cowbirds avoided the
302   windows in 29.4% (5 of 17) of trials and were adjudged to collide with the windows in
303   70.6% (12 of 17) of these flight trials (right pair of bars on Figure 7). Taken together, the
304   cowbirds were at least 30% less likely to collide with a window if the windows were
305   treated with the BirdShades product compared with the control product ($Z = 3.29$, $N = 17$
306   pairs, $p = 0.001$; Figure 7). However, that number could be larger as we did not observe any
307   avoidance in the control trials. It could be argued that the BirdShades treatment improved
308   avoidance by a very large magnitude compared to zero avoidance in the control treatment.
309   Due to digitization issues with some calibration files, the sample size of videos we
310   could analyze for flight velocity of cowbirds was reduced. There were few birds where we
311   had a measurement of flight velocity in all three treatments. Hence, we decided to adopt an
312   alternative linear model approach with the time sequence during a video as a repeated-
313   measures factor but treatment as an among-subjects factor due to lack of replication of the
314   same bird across all treatments. This analysis indicated that, as with the zebra finches, the
315   cowbirds decelerated as they approached the windows ($F_{2,62} = 40.09$, $p < 0.001$) and that

316 there was a non-statistically supported trend for the cowbirds to fly approximately 25%
317 slower when presented with a BirdShades treated window ($F_{2,31}$ =2.59, p = 0.091; Figure 8).
318 As with the zebra finches, the cowbirds adjusted their velocity early in their flight and
319 decelerated at similar rates across treatments (Figure 8).
320

Discussion

322 Our data indicate that zebra finches and brown-headed cowbirds are more likely to avoid a
323 harmful collision with a window if the window is externally treated with the BirdShades
324 film. As we compared collision risk to a control treatment that also received a window film
325 but that was not reflective in the shorter (ultraviolet) wavelengths of light, we can further
326 conclude that increased surface reflection in the ultraviolet ends of the avian-visible
327 spectrum assists with avoiding window collisions. This conclusion does not preclude that
328 other 'colors' of reflected light might also be important. As many avian species are sensitive
329 to ultraviolet light, but especially small passerines (Hart, 2001; Aidala et al., 2012), this
330 observation indicates that the BirdShades film could help protect birds from window
331 collisions in many localities.
332   Not only was the overall risk of collision reduced for both zebra finches and brown-
333 headed cowbirds when the BirdShades film coating was applied to the windows, but the
334 velocity of flights was also reduced by approximately 25% during the last 0.5 s of flight. As
335 the birds were close to the windows during this video sequence, the reduction in flight
336 velocity is most parsimoniously explained as an effect of the window treatments. This may
337 mean that when a collision occurs in nature it will be with less force and, therefore, less
338 likely to cause irreparable damage to the bird. Obviously, we did not allow the birds to
339 actually strike the windows in our flight tunnel, but the deceleration we observed indicates
340 a protective value of window treatments that has not been quantified in other studies.
341   In part of our study, we presented birds with an industry-standard forced choice
342 test (i.e. our 'both' treatment) where the control and treatment windows were presented
343 side-by-side in the same flight trial (cf. Rössler, Nemeth & Bruckner, 2015; Sheppard,
344 2019). In separate flight trials we presented the birds with situations where all windows in
345 a trial were either control or BirdShades-treated. We argue that the latter type of
346 comparison, where all of the windows in a trial have been treated with the same film, is
347 more ecologically salient as it will be common that adjacent windows on a building will be
348 treated in the same manner (Hager et al., 2013). It would be a rare situation where birds
349 would make an instantaneous choice between windows that have been treated differently
350 and those windows are presented side-by-side, as in the 'both' treatment. Of note, the effect
351 size in the more ecologically-relevant comparison of flight in the 'control' versus
352 'treatment' trials is consistently smaller (approximately 50% in zebra finches and 30% in
353 brown-headed cowbirds) than that estimated in the forced choice situation of the 'both'
354 trials (approximately 90% in zebra finches and 75% in brown-headed cowbirds). These
355 observations suggest that many previously published estimates of effect sizes, that have
356 used forced choice paradigms (eg. Rössler, Nemeth & Bruckner, 2015; Sheppard, 2019),
357 might also be over-estimating the efficacy of collision-reduction technologies. Therefore,
358 we urge caution in applying data from forced choice trials in predicting any effects in
359 changing the rate of collisions with windows in common in-situ conditions. If we take the
360 effect size we have isolated in these more ecologically-relevant trials at face value, a

361 reduction in bird collision rate of 30-50% would still offer substantial protective value and
362 potentially avoid millions of bird deaths annually.
363   As far as we are aware, our experiment may be the first to document the
364 effectiveness of any external window treatment on the risks of window collision when the
365 birds are flying in lighting conditions that realistically replicate those of a day-lit building
366 window with indoor lighting. The sensory ecology of birds will be greatly affected by
367 lighting conditions and influence the ways in which the birds perceive and attempt to avoid
368 collision risks (Martin, 2011). Specifically, we ensured that the external surface of the
369 windows received ambient daylight, which is rich in shorter-wavelength light at all times of
370 this study, while also illuminating the internal surface of windows with representative
371 artificial light. The interplay of the external and internal lighting conditions with the
372 reflective and absorptive properties of the window (plus film and glue applied) will affect
373 whether the birds perceive the window as a reflection, a solid structure, or otherwise. We
374 contend that many other flight tunnel tests that have not exposed birds to realistic lighting
375 conditions, most notably those that fly the birds in dark tunnels without daylight on the
376 external surface (i.e. birds' side) of windows (Rössler, Nemeth & Bruckner, 2015; Sheppard,
377 2019), have limited application to reducing window collisions in daylight conditions. Their
378 results might apply to interpreting how birds respond to lit windows during night flights,
379 depending on whether the internal surface of those windows has been illuminated with
380 suitable artificial lighting.
381   Other than illustrating the apparent effectiveness of the BirdShades film product, we
382 propose this study raises methodological issues that can contribute to the development of
383 window collisions testing standards. We advocate that scientists and industry collaborates
384 to develop standardized methodology for testing and comparing the effectiveness of
385 collision-reducing technology. Further, we highlight the following conditions, which are
386 currently not commonplace in window collision testing. First, if flight tunnels are used, they
387 must attempt to simulate more naturalistic ecological conditions for birds, including
388 realistic internal and external lighting conditions and they should avoid forced-choice
389 window trials but instead present trials in which all windows are treated the same way in a
390 no-choice design. Birds will rarely experience a forced-choice situation in nature and our
391 data indicate that forced-choice measurements likely overestimate the effectiveness of
392 technologies.
393   Methodological design of window-collision tests must account for other additional
394 factors. In constructing treatment groups in flight tunnel tests, we advocate for the use of
395 positive control trials in which the windows are manipulated but not treated with the
396 specific film coating that will be tested. This allows the experimenter to understand the
397 influence of the general presence of film and glue independently of the precise reflective
398 and absorptive properties of the test film. In this study we used a transparent film as a
399 positive control. Negative controls, where windows are entirely untreated cannot
400 deconfound other associated factors (e.g. presence of film and adhesive, or general
401 alteration of the surface of glass). If only one control treatment is possible, we advocate for
402 the use of positive controls. Further, when exposing birds to the experimental treatments,
403 we advocate for the inclusion of repeated-measures designs where possible. By exposing
404 the same individuals to all treatments it is possible to minimize the effects of among-
405 individual variance in behavior, motivation, and physiological state on the metrics of
406 collisions. Repeated-measures approaches have proven useful in many other contexts

407   (Shaffer, 1979; Swaddle, 1997; Swaddle & Biewener, 2000; Boulton et al., 2015) but have
408   yet to be applied to the collisions literature. Importantly, this allows the experimenter to
409   employ smaller sample sizes, potentially reducing the cost and time involved in adequately
410   testing products. By making window collisions testing more affordable and efficient we
411   might gain more information about the efficacy of products. It is possible to employ
412   repeated-measures designs in field trials, if birds are individually color-banded and those
413   birds are resident within the area.
414   In addition to the aforementioned points, again applied to flight tunnel tests, we
415   should continue to compare the performance of recently wild-caught individuals to
416   performance of captive-reared birds. This will help us to understand the influence of prior
417   housing and stress levels on metrics of collisions. Finally, where possible, we recommend
418   that experimenters assess the velocity of flight and/or the force of collisions. In our study
419   we showed that flight velocity can be lowered even when collisions are still likely to occur.
420   By gaining more information about the impacts of any potential collision we can be more
421   precise in predictions about how birds will be affected.
422   Avian collisions with windows are an issue of importance to global conservation as
423   perhaps up to a billion birds die each year when they fly into closed windows (Klem, 2014;
424   Loss et al., 2014; Loss, Will & Marra, 2015; Ocampo-Peñuela et al., 2016; Schneider et al.,
425   2018) and the problem is geographically widespread (Basilio et al., 2020). Though external
426   window treatments are generally affordable they can be expensive to apply if not affixed to
427   windows at the time of building construction. The high cost is often associated with getting
428   access to a high-story external window surface. If the films can be made durable, they are
429   promising solutions if planned for with sufficient forethought. In North America, there have
430   been recent calls for and some legislative action to require bird-friendly glass on buildings
431   (eg., 2020 legislation in New York City, US) but it is unclear how this will be achieved,
432   especially as the tinted glass can be more expensive than other options. Externally-applied
433   products, such as the one we tested from BirdShades, could play an affordable role in
434   solutions but only if we test the products in ways that are realistic with how birds interact
435   with windows in nature. Hence, there is pressing need to evaluate, using the criteria we
436   describe above, externally-applied window films and glass that is tinted in particular
437   spectral ranges in order to provide affordable, sustainable, and effective conservation
438   solutions.
439   Overall, we advocate for the continued use of flight tunnel tests as they offer
440   controlled conditions that are more easily replicated by different research groups. Such
441   flight tunnel tests need to be adapted to deliver realistic lighting conditions (on both
442   external and internal surfaces of windows) and not use forced choice experimental designs.
443   Further they should employ appropriate positive controls and, when possible, use
444   repeated-measures approaches so that studies can further isolate the effects of any window
445   treatments. However, these flight tunnel tests should be accompanied with field testing
446   that meets similar rigorous experimental standards but place the windows in the actual
447   context that birds experience—on real buildings. We have yet to perform field tests with
448   the BirdShades product.
449
450   **Conclusions**

451 Overall, our data support a conclusion that the BirdShades external window film reduces
452 the risk of collision by zebra finches and brown-headed cowbirds by approximately 30-
453 50%. It could be claimed that these estimates should be higher, according to the outcomes
454 of the forced choice trials (perhaps 80- 90%), but we interpret the forced choice design to
455 lack ecological relevance and over-estimate what is more likely to happen in the field. This
456 is a deficit of the flight tunnel testing window-collisions literature in general. Furthermore,
457 when collision does occur, it is likely that the birds will strike the windows with less force
458 as the BirdShades film treatment results in 25% reduction in flight velocity close to the
459 point of impact. Therefore, we propose that the BirdShades product could be largely
460 effective in mitigating and preventing window collisions, particularly for the large number
461 of avian species who are sensitive to shorter wavelengths of light. It is important that this
462 flight tunnel testing is supported by installations on buildings so that the actual effects on
463 avian mortality can be documented. Further, we advocate for researchers and industry to
464 collaborate in devising standards for assessing window collisions, and start this discussion
465 by suggesting several important features that are not yet commonly incorporated into
466 flight tunnel testing.
467

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473

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475 ## References

476 Aidala Z, Huynen L, Brennan PLR, Musser J, Fidler A, Chong N, Machovsky Capuska GE,
477   Anderson MG, Talaba A, Lambert D, Hauber ME. 2012. Ultraviolet visual sensitivity in
478   three avian lineages: paleognaths, parrots, and passerines. *Journal of Comparative*
479   *Physiology A* 198:495–510. DOI: 10.1007/s00359-012-0724-3.Basilio LG, Moreno DJ,
480   Piratelli AJ. 2020. Main causes of bird-window collisions: A review. *Anais da Academia*
481   *Brasileira de Ciencias* 92. DOI: 10.1590/0001-3765202020180745.
482 Boulton K, Couto E, Grimmer AJ, Earley RL, Canario AVM, Wilson AJ, Walling CA. 2015.
483   How integrated are behavioral and endocrine stress response traits? A repeated measures
484   approach to testing the stress-coping style model. *Ecology and Evolution* 5:618–633. DOI:
485   10.1002/ece3.1395.
486 Hager SB, Cosentino BJ, McKay KJ, Monson C, Zuurdeeg W, Blevins B. 2013. Window Area
487   and Development Drive Spatial Variation in Bird-Window Collisions in an Urban
488   Landscape. *PLoS ONE* 8. DOI: 10.1371/journal.pone.0053371.Goldsmith TH, Butler BK.
489   2005. Color vision of the budgerigar (Melopsittacus undulatus): Hue matches,
490   tetrachromacy, and intensity discrimination. *Journal of Comparative Physiology A:*
491   *Neuroethology, Sensory, Neural, and Behavioral Physiology* 191:933–951. DOI:
492   10.1007/s00359-005-0024-2.
493 Hager SB, Cosentino BJ, McKay KJ, Monson C, Zuurdeeg W, Blevins B. 2013. Window Area

494   and Development Drive Spatial Variation in Bird-Window Collisions in an Urban
495   Landscape. *PLoS ONE* 8. DOI: 10.1371/journal.pone.0053371.
496 Hart NS. 2001. The Visual Ecology of Avian Photoreceptors. *Progress in Retinal and Eye*
497   *Research* 20:675–703. DOI: 10.1016/S1350-9462(01)00009-X.
498 Jackson BE, Evangelista DJ, Ray DD, Hedrick TL. 2016. 3D for the people: Multi-camera
499   motion capture in the field with consumer-grade cameras and open source software. *Biology*
500   *Open* 5:1334–1342. DOI: 10.1242/bio.018713.
501 Klem D. 2009. Preventing bird–window collisions. *The Wilson Journal of Ornithology* 121:314–
502   321. DOI: 10.1676/08-118.1.
503 Klem D. 2014. Landscape, Legal, and Biodiversity Threats that Windows Pose to Birds: A
504   Review of an Important Conservation Issue. *Land* 3:351–361. DOI: 10.3390/land3010351.
505 Klem D. 2015. Bird-Window Collisions: A Critical Animal Welfare and Conservation Issue.
506   *Applied Animal Welfare Science* 18. DOI: 10.1080/10888705.2015.1075832.
507 Klem D, Saenger PG. 2013. Evaluating the effectiveness of select visual signals to prevent bird-
508   window collisions. *The Wilson Journal of Ornithology* 125:406–411. DOI: 10.1676/12-
509   106.1.Lind O, Mitkus M, Olsson P, Kelber A. 2013. Ultraviolet sensitivity and colour vision
510   in raptor foraging. *Journal of Experimental Biology* 216:1819–1826. DOI:
511   10.1242/jeb.082834.
512 Loss SR, Will T, Loss SS, Marra PP. 2014. Bird–building collisions in the United States:
513   Estimates of annual mortality and species vulnerability. *The Condor* 116:8–23. DOI:
514   10.1650/CONDOR-13-090.1.
515 Loss SR, Will T, Marra PP. 2015. Direct Mortality of Birds from Anthropogenic Causes. *Annu.*
516   *Rev. Ecol. Evol. Syst* 46. DOI: 10.1146/annurev-ecolsys-112414-054133.
517 Martin GR. 2011. Understanding bird collisions with man-made objects: A sensory ecology
518   approach. *Ibis* 153:239–254. DOI: 10.1111/j.1474-919X.2011.01117.x.
519 Ocampo-Peñuela N, Winton RS, Wu CJ, Zambello E, Wittig TW, Cagle NL. 2016. Patterns of
520   bird-window collisions inform mitigation on a university campus. *PeerJ* 4. DOI:
521   10.7717/peerj.1652.
522 Rössler M, Nemeth E, Bruckner A. 2015. Glass pane markings to prevent bird-window
523   collisions: less can be more. *Biologia* 70:535–541. DOI: 10.1515/biolog-2015-0057.
524 Schneider RM, Barton CM, Zirkle KW, Greene CF, Newman KB. 2018. Year-round monitoring
525   reveals prevalence of fatal bird-window collisions at the Virginia Tech Corporate Research
526   Center. *PeerJ* 6:e4562. DOI: 10.7717/peerj.4562.Shaffer JW. 1979. On the analysis of
527   repeated measures over time in medical, pharmacological, and behavioral research. *Journal*
528   *of Behavioral Medicine* 2:221–238. DOI: 10.1007/BF00844920.
529 Sheppard CD. 2019. Evaluating the relative effectiveness of patterns on glass as deterrents of
530   bird collisions with glass. *Global Ecology and Conservation*. DOI:
531   10.1016/j.gecco.2019.e00795.
532 Swaddle JP. 1997. Within-individual changes in developmental stability affect flight
533   performance. *Behavioral Ecology* 8:601–604. DOI: 10.1093/beheco/8.6.601.
534 Swaddle JP, Biewener AA. 2000. Exercise and reduced muscle mass in starlings. *Nature* 406.
535   DOI: 10.1038/35020695.
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537

Figure 1

Schematic of the flight tunnel.

Each bird was released in the dark tunnel (left) and flew to the day-lit flight corridor (right) and collided with a fine mist net before interacting with the two windows. A stlyized flight trajectory is shown in red. The camera icons represent GoPro cameras through which we recorded all flights.
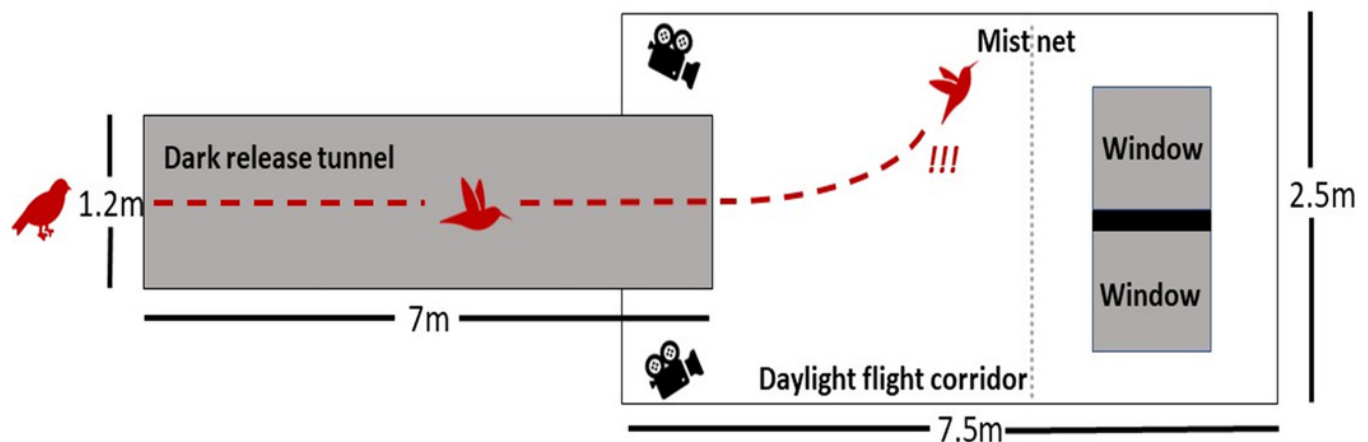
Figure 2

Example irradiance spectral profile of the light received (A) at the external and (B) the internal surface of windows during flight trials.

The color scheme above the graph indicates human visible colors relative to wavelength of light. Daylight (A) is rich in all visible wavelengths but peaks in the shorter wavelength ranges. The interior lighting (B) also peaked at shorter wavelengths and was far less intense than daylight.

A

B
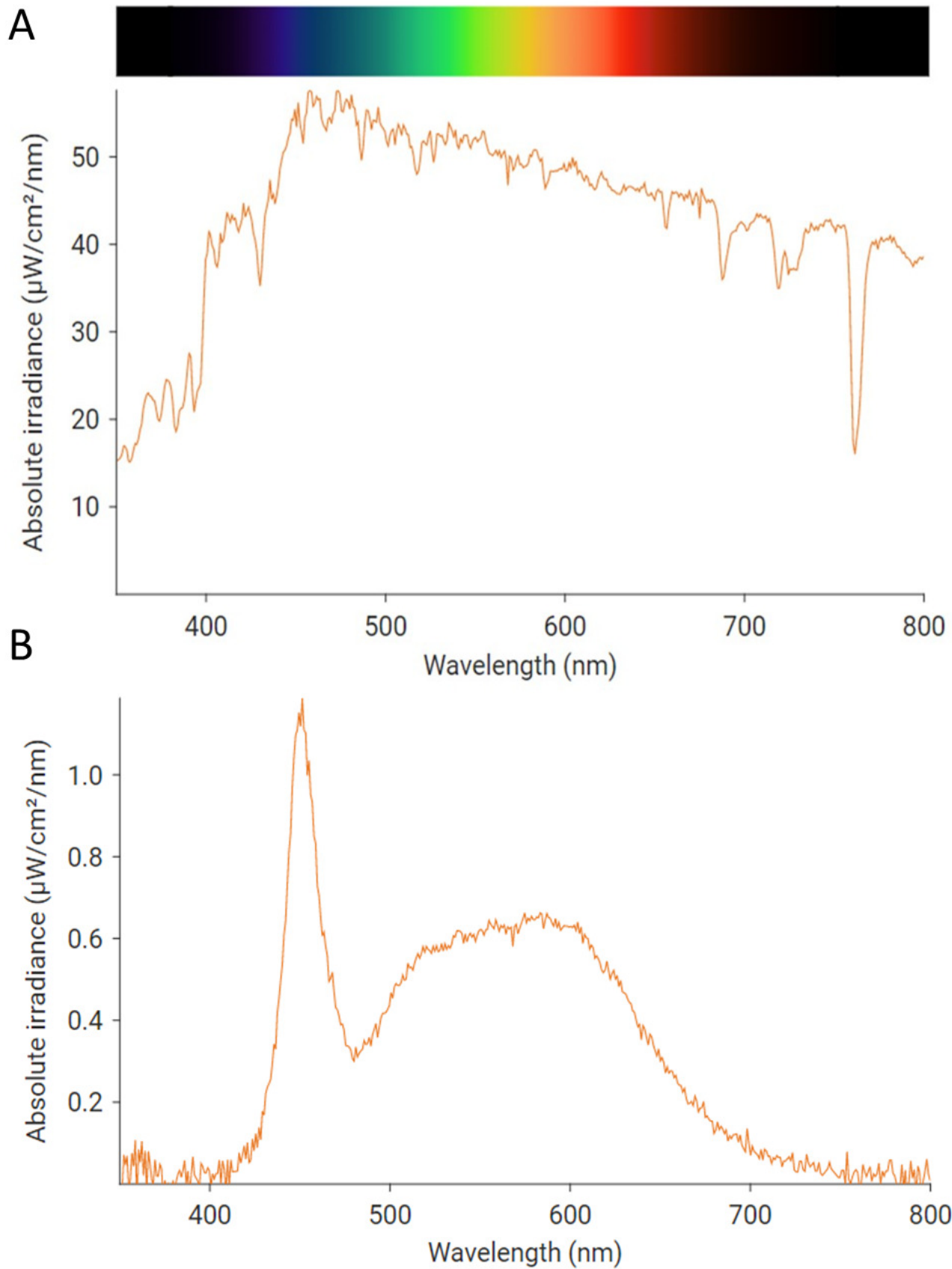
Figure 3

The proportion of flights in which zebra finches were adjudged to collide with a control or a treatment window, in forced-choice 'both' trials.

For zebra finches, there was a 91% reduction in collision risk when windows were treated with the BirdShades product compared with the control product.
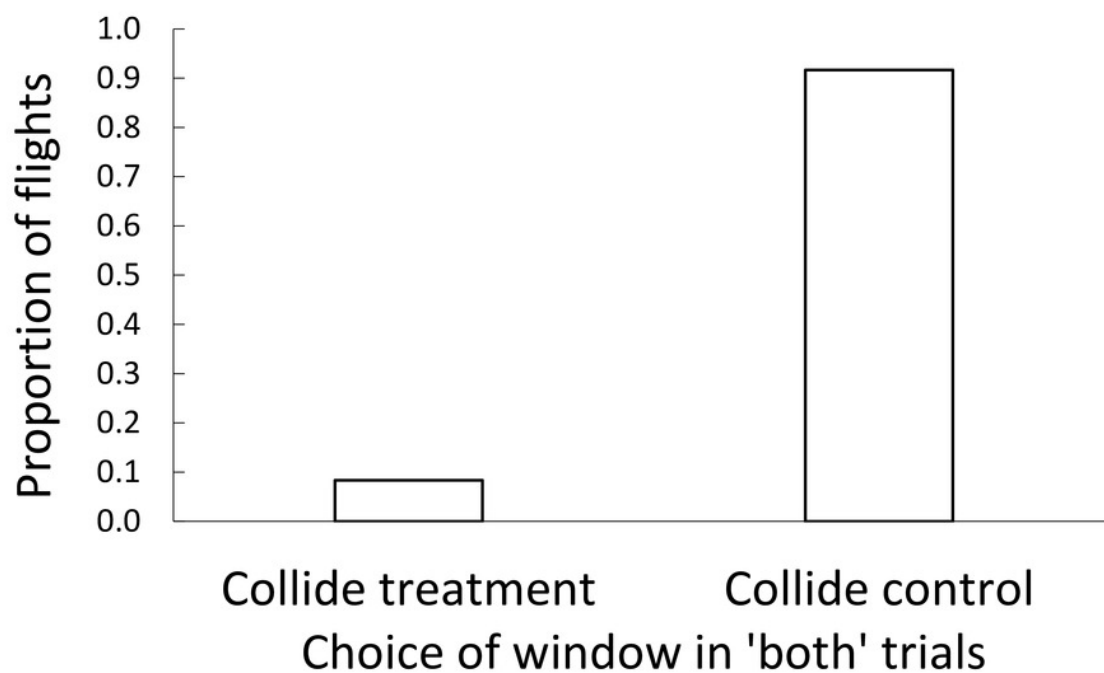
Figure 4

Proportion of flights when zebra finches were adjudged to collide with windows (open bars) or avoid windows (filled bars) in either the control or treatment trials.

The zebra finches were approximately 50% less likely to collide with a window if the windows were treated with the BirdShades film compared with the control film
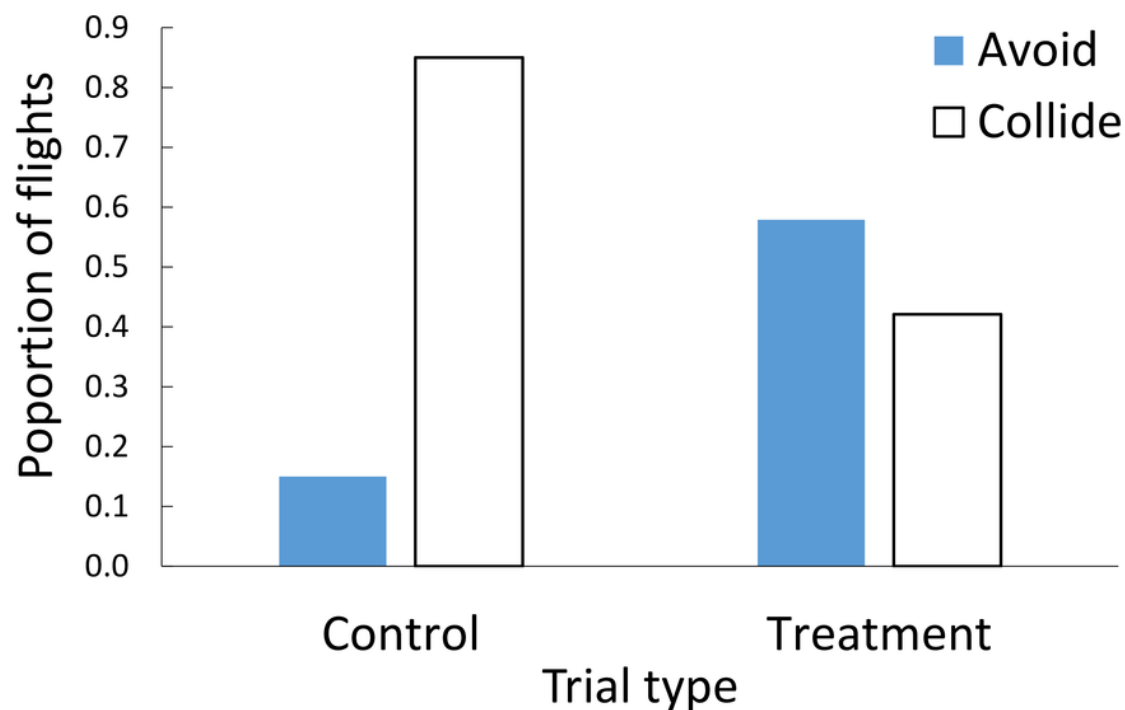
Figure 5

Mean (± 95% CI) flight velocity across sequential five frames of flight (15-11, 10-6, 5-1, counting from the end of flight) for zebra finches.

Treatment groups are as follows, control (filled squares), treatment (hollow triangles), and both (hollow circles) trials. Lines connecting points are least-squares lines of best fit. Zebra finches flew approximately 25% slower when the windows were treated with the BirdShades film compared with the control condition.
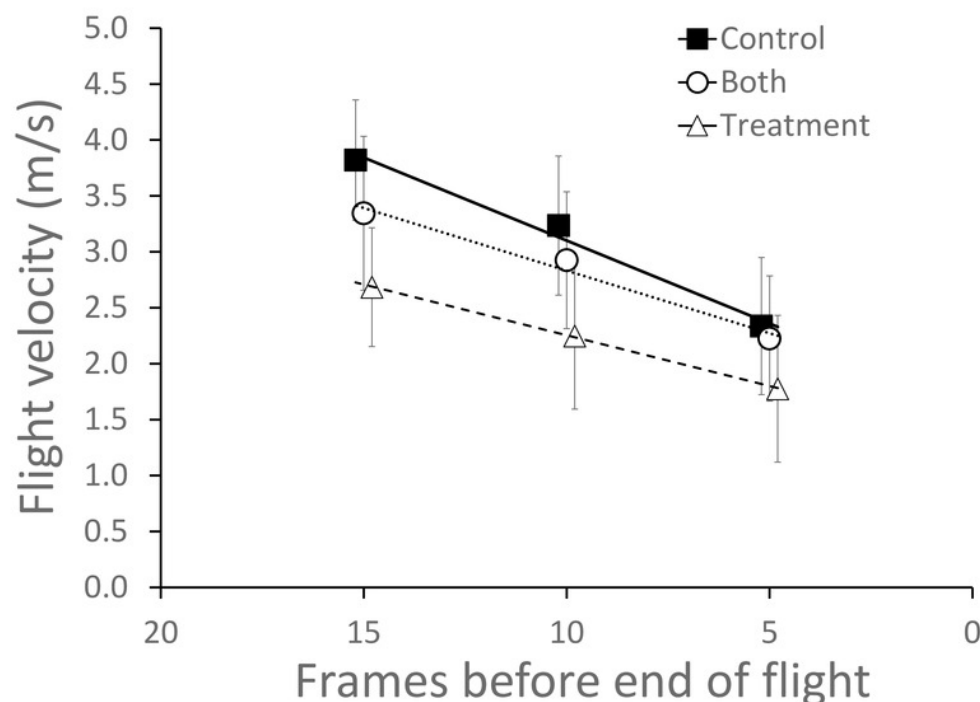
Figure 6

The proportion of flights in which brown-headed cowbirds were adjudged to collide with a control or a treatment window, in forced-choice 'both' trials.

Brown-headed cowbirds experienced a 75% reduction in the risk of collision under the BirdShades compared with the control treatment.
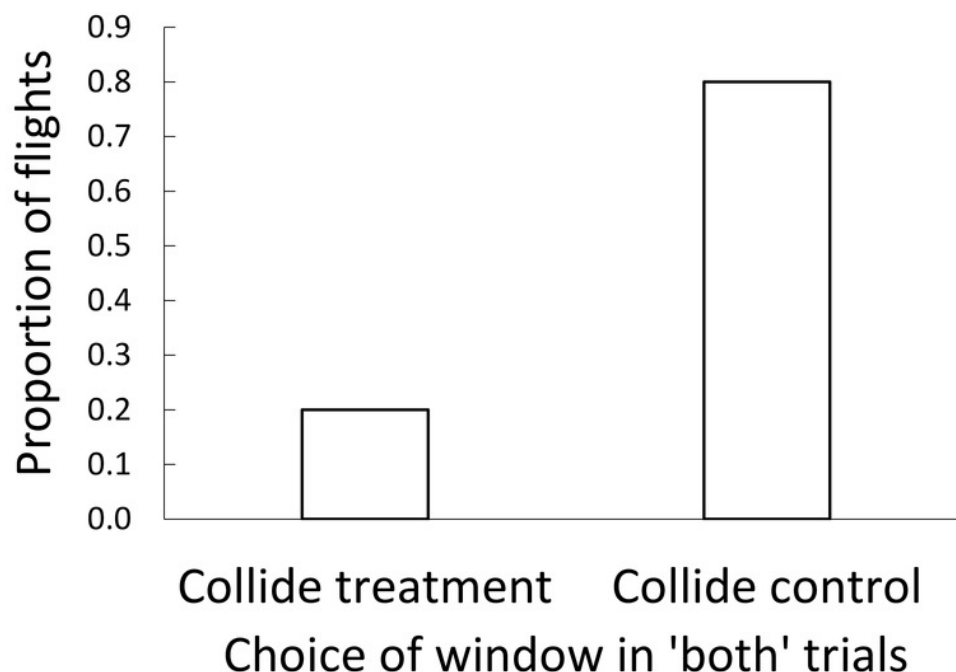
Figure 7

Proportion of flights when brown-headed cowbirds were adjudged to collide with windows (open bars) or avoid windows (filled bars) in either the control or treatment trials.

Brown-headed cowbirds were at least 30% less likely to collide with a window if the windows were treated with the BirdShades product compared with the control product.
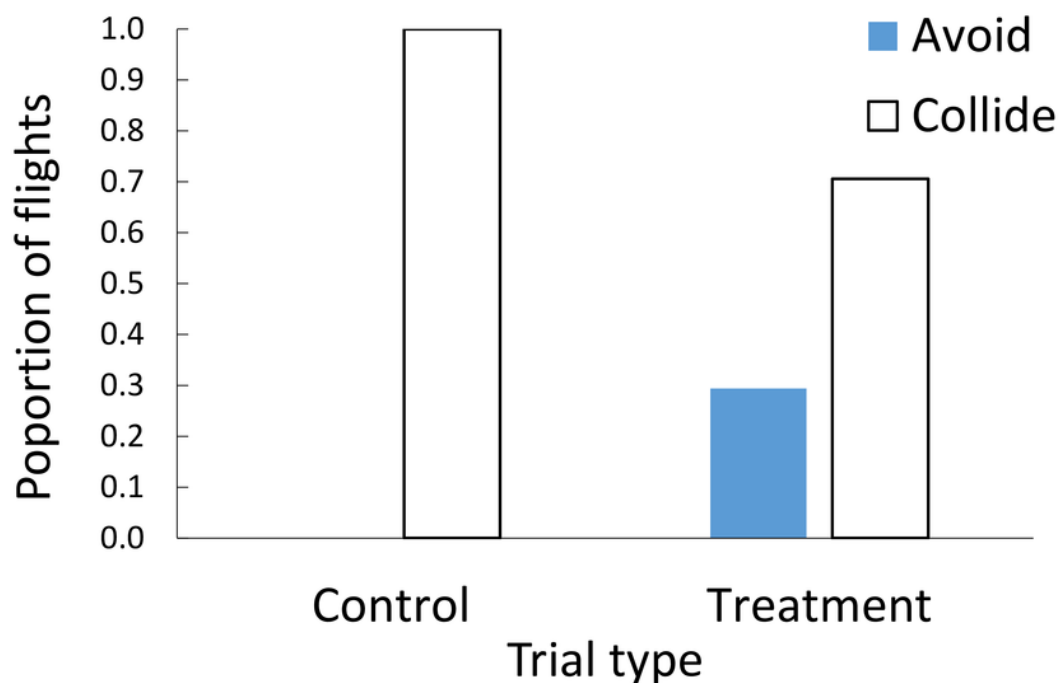
Figure 8

Mean (± 95% CI) flight velocity across sequential five frames of flight (15-11, 10-6, 5-1, counting from the end of flight) for brown-headed cowbirds.

Treatment groups are as follows, control (filled squares), treatment (hollow triangles), and both (hollow circles) trials. Lines connecting points are least-squares lines of best fit. There was a non-statistically supported trend for the brown-headed cowbirds to fly approximately 25% slower when presented with a BirdShades treated window compared with controls.