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Evaluating the relative effectiveness of patterns on glass as deterrents of bird collisions with glass

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ABSTRACT

Studies documenting bird mortality from collisions with glass on buildings estimate hundreds of millions of birds die each year in North America from this cause alone. To reduce this mortality, it is essential to provide an objective assessment of the relative collision threat posed by glass and other materials incorporating patterns intended to deter collisions, similar to ratings for insulation value and breaking strength, for use by building professionals such as architects, engineers, planners, and other decision makers. We wanted to determine whether we could use a non-injurious binomial choice test developed in Austria, with local bird taxa in Pennsylvania, to provide objective collision threat ratings. Preliminary work in 2010-11 tested three patterns tested in Austria in 2004-6 and produced virtually identical scores leading to the conclusion that the test should apply generally to passerines. Additional trials indicated that variables including dimensions of pattern elements, spacing and orientation may interact in producing tunnel scores. The tunnel test has the potential to: a) determine how size, orientation and spacing of pattern elements impact collision-reduction effectiveness, b) rate commercially available glass, and c) evaluate new bird-friendly technologies.

1. Introduction

1.1. A deadly threat to birds

Concern about the negative impact of collisions with glass on bird populations has paralleled glass manufacturing developments producing larger, cheaper panels of glass for construction of structures from homes to skyscrapers (Klem, 2010; Sheppard, 2011). An early estimate (Klem, 1990) approximated up to a billion birds a year killed annually by glass in the U.S. Subsequent information (Dunn, 1993) supported the magnitude of that estimate. Techniques of meta-analysis (Loss et al., 2012) set the stage for improved quantification of bird mortality from collisions with glass and other anthropogenic threats. Loss et al. (2014) collected data on glass collisions from the literature, museums, monitoring programs, and other sources. Data sets were carefully vetted and filtered to ensure they could be used in single analyses. The authors calculated an annual median value for mortality at homes (one to three story buildings) at 253 million, 2.1 birds per structure, or 44% of total mortality. Median annual mortality at low rise buildings (4-11 stories), was estimated as 339 million, 21.7 birds per building. High rises, causing least annual mortality as a category (508 000), individually had the highest median rate: 24.3 birds per building. Loss produced a median estimate of overall mortality of 599 million birds killed annually in the U.S. ranging

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from 365 to 988 million. These numbers have confirmed reducing bird mortality caused by glass as conservation priority for American Bird Conservancy (Sheppard, 2011; Sheppard and Phillips, 2015), USFWS (https://www.fws.gov/birds/bird-enthusiasts/threats-to-birds/collisions/buildings-and-glass.php), and other conservation organizations.

1.2. Human and avian visual ecology

Many humans believe they can see glass but in reality learn a concept of glass as a solid, transparent/reflective material from experience, early in life (Gibson and Walk, April 1960). Cues like mullions, door/window frames, and right angles indicate where to expect glass - and people still hit glass fairly often. Birds can and do learn about particular pieces of glass. For example, zoos with glass-fronted exhibits make glass visible, using soap or other materials, for several days after new birds are introduced. The markings are then removed and birds do not subsequently fly into the glass (author personal experience). However, birds do not grasp the *concept* of glass as a transparent or reflective barrier and cannot apply the types of cues that humans use. A row of decals telling people ‘glass wall here’ is to birds a row of obstacles to fly above, below, or between. Effective markers that cause birds to change trajectory must be two- or three-dimensional signals with correct spacing that themselves are what birds will perceive and avoid.

1.3. Historical solutions

There is a history of recommendations for averting collisions on individual windows (reviews in Klem, 1991; Schleidt et al., 2011), including placing decals, tape or other materials on glass and dangling feathers, cords and other materials in front of glass, but most suggested solutions were without documentation of effectiveness. NYC Audubon (2007), (Chicago Bird Collision Monitors, 2007), Fatal Light Awareness Program Canada (FLAP Canada, 2007) and others published early recommendations for ‘bird-friendly design’ to architects, based on common sense or educated guesswork, because the necessary science did not exist. Because these were largely qualitative, *e.g.*, ‘increase visual noise’, ‘don't use large expanses of glass', they were difficult for architects to apply or to use for determination of compliance. As interest in bird-friendly materials increased, attempts began to find ways to evaluate and compare solutions. This has been facilitated by recent emphasis on avian visual ecology and navigation through cluttered environments.

1.4. Avian sensory ecology explains problems and suggests solutions

Sensory ecology of birds differs from that of humans in so many major ways that it can be difficult for humans to fully understand the causes of collisions with glass (Martin, 2011) and to design solutions to stop them. Most birds have eyes on the sides of the head, little overlap of visual fields, and modest three-dimensional vision that is obstructed to various degrees by the bill (Martin, 2011, 2012). Unlike humans, who tend to focus on what is in front of them, birds look to the side for information concerning flight speed (Bhagavatula et al., 2011, Dakin et al., 2016, Martin, 2009; Schiffner and Srinivasan, 2015), and behind them. Birds see many more colors than humans (Land and Nilsson, 2010) and can perceive the earth's magnetic field. However, perhaps as a functional trade off, birds have poor contrast sensitivity compared to humans, meaning that humans are better at distinguishing between objects at a distance than birds (Boström et al., 2016; Kiltie, 2000; Ghim and Hodos, 2006).

Compared to the study of migratory flight, knowledge of smaller scale navigation has only recently been a research focus. While little of this work is intended to relate specifically to collisions with glass, results can still be relevant to that issue. For example, work with budgies (*Melopsittacus undulates)* (Schiffner et al., 2014, Vo et al., 2016) flying through gaps of different widths in lighted tunnel, showed birds were accurately aware of their own wingspans and could be seen to modify the position of their wings depending on the width of a gap in their path. This directly relates to the design of patterns intended to deter collisions. Because small songbirds are frequent victims, patterns must have relatively narrow spacing, related directly to bird body size.

Ros et al. (2017) found that pigeons (*Columba livia*) exhibited limited steering and chose gaps between an array of horizontal obstacles most aligned to their immediate flight direction, in contrast to birds navigating through arrays of vertical obstacles (Lin et al., 2014) that favored steering to the widest gap. Both studies were intended to help programming of robots navigating cluttered environments, but may also explain asymmetry of responses by birds to the same pattern oriented vertically versus horizontally. It also reinforces the relationship between body size of potential collision victims and spacing necessary to create effective deterrent patterns.

Lin et al. (2014) found that pigeons adjusted their flight path approximately 1.5 m from the closest obstacle, suggesting ‘a reactive mode of path planning’. Blackwell et al., (2009), working on bird-aircraft collisions, studied reaction times of Brown-headed Cowbirds, (*Molothrus atus)*, faced with perceived danger from rapidly approaching vehicles and found that they could not react in time to escape. For glass collisions, these findings translate to a need for deterrent patterns to be visible at a distance sufficient for less agile passerines like thrushes to change to a safe route.

1.5. Evaluating proposed solutions

Reducing bird mortality from glass collisions is a challenge that cannot be met by science alone. Thousands of new commercial structures and homes are constructed every year (Center for Sustainable Systems, University of Michigan, 2018;

U.S. Census Bureau, 2019) continually adding threats to birds. To stem this increase and begin to address existing glass, we need to educate architects, developers, glass manufacturers, engineers, politicians and the public and provide readily available tools that can produce structures safe for birds, as well as functional and esthetically satisfying. Conservation biologists must learn the vocabulary of building construction to provide thoughtful and practical solutions and design strategies. Fundamental to accomplishing this is creating a system of evaluation that rates level of threat to birds, analogous to those used to rate other qualities of glass, like thermal performance and breaking strength.

Ideally, evaluation of a bird-friendly solution might involve monitoring thousands of square meters of glass on multiple structures for several years, both before and after a proposed solution was installed to replace original glass. However, this would require an impractical level of manpower, expense and time to produce results for a single solution. Besides anecdotal accounts, in only a few cases (FLAP Canada, 2018), has glass been adequately monitored before and after remediation (but not replacement). This approach could not generate a sufficient number of rated options to allow bird-friendly architecture to become mainstream.

Klem was the first to publish a protocol for evaluating proposed solutions. He erected a series of framed glass ‘windows’ with different treatments, (including an untreated control), and associated bird feeders, at a woods/field boundary in LeHigh County, Pennsylvania. Collisions and mortality rates for each sample type are documented and compared to that for the control glass (Klem, 1990, 2009; Klem and Saenger, 2013). This testing program is still active as of 2019.

1.6. The ‘tunnel’ test protocol

In 2000, at the request of the firm Glaswerke Arnold GmbH & Co KG (Neusser Str. 1, 91732 Merkendorf) the Max Planck Institute began trials of glass with different UV reflecting patterns as potential collision deterrents (Ley, 2006; Fiedler and Ley, 2013). They used a non-injurious, indoor binomial choice protocol, giving netted, local birds a choice to fly towards plain or patterned glass but using a net to prevent contact with glass. This strategy allowed testing each sample with a known number of birds of known species. The project ceased operating in 2011.

In 2004, the Hohenau-Ringelsdorf Biological Station (Hohenau) in Austria debuted an outdoor protocol to compare effectiveness of different patterns on glass for preventing bird collisions (Rössler, 2005, 2015; Rössler and Zuna-Kratky, 2004; 2007). The Hohenau ‘tunnel’ is also a binomial choice protocol. Birds, protected by a net, have the option to ‘exit’ by flying either towards a test sample or unmarked control glass, seen at the far end of a dark, enclosed space (Fig. 1). Rössler's tunnel was constructed (and is still operating) at Hohenau, a bird banding station, where netting migratory birds makes it possible to test large numbers of samples in a relatively short period of time. This protocol has also been adopted as the official standard for testing free-standing glass in Austria (Austrian Standards Institute, 2010).

There are advantages and drawbacks to the testing protocols described above (for a comprehensive review, see Seewagen, 2011). Because the binomial choice protocols use netted birds, the number of flights per material is controlled and species composition is known, with large numbers of test subjects possible when studies are done at a banding station. The Klem protocol depends on the chance that free-flying birds will have a glass panel in their flight path. Feeders are used to increase the odds, but not all strikes leave evidence (Klem, 2009) and birds that swerve to avoid glass go unrecorded. While subjects in the tunnel protocol are protected by a net and released after a flight, Klem's subjects are often injured or killed (Klem, 2009). This may produce a negative impact on the local bird population. However, structures with glass are continually changing local bird populations everywhere, and use of control glass permits direct comparison of samples in the same trial.

Birds in the choice protocols fly to escape their enclosure, and may be stressed by netting and handling, where Klem's subjects are not. However, as Seewagen points out, many collisions on homes take place when birds are flushed from feeders near windows (Klem, 1991; Dunn, 1993) and those birds are likely to be stressed as well. However, Rössler et al. (2015) and

Fig. 1. The ‘testing tunnel’ at the Carnegie Museum's Powdermill Avian Research Center.

Sheppard (2019) show that results for control patterns are consistent from year to year, so if there is a stress effect, it is also consistent and does not preclude comparison of results among seasons. Test results for tunnel-type tests can only be considered an index of effectiveness, not a direct measure.

Klem's glass panels stand in the open and birds may see reflections on the panels as light changes throughout the day. Reflections change with the angle of view but presumably, most of Klem's subjects fly directly from the nearby feeder at an angle normal to the plane of the glass, as is the case with the binomial choice protocol. However, the binomial choice protocols described above do not create reflections on the glass, and that issue must be evaluated separately.

The Klem protocol approximates windows on a dwelling, but it is specific to one location in Pennsylvania. Because there is an enormous diversity of geographical locations and habitats, the protocol cannot be said to be generally representative. The binomial choice protocols attempt to standardize test conditions and create an index or relative rating, to permit comparison among tested materials.

The author elected to work with the Hohenau tunnel protocol because it can evaluate more samples per season. In addition, the tunnel provides an objective basis for rating the relative degree of threat posed by glass incorporating proposed solutions. Because the test uses birds that have just been netted and measured, it is likely that the test subjects are moderately stressed at the time of testing. However, Rössler et al. (2015) and Sheppard (2019) showed that results are consistent from year to year, so stress may be a factor, but not a bias. This still permits comparison among different samples.

1.7. The tunnel protocol is a good tool for evaluating solutions

We wanted to determine whether we could use this protocol with local bird taxa, at the Powdermill Avian Research Center in Pennsylvania (PARC), to provide objective collision threat ratings consistent with those from Hohenau, in spite of using different bird taxa at a different location. This could provide a basis for guidelines attempting to define 'bird-friendly design', a relatively simple way to gauge the reactions of birds to complex visual cues intended to change their flight direction, that may incorporate a mix of different signals. The tunnel does not model any specific environment, but uses standard conditions to produce an index, allowing the comparison of different materials. 'Threat factor' of a material is defined as percent flights to the test glass side. Threat factors are an index of relative effectiveness, not a measure of absolute effectiveness, because there is no available field data to use to calibrate the relationship.

2. Methods

2.1. Test protocol

A glass-evaluation tunnel at Carnegie's Powdermill Avian Research Center (PARC) (see Fig. 1). The design followed blueprints for Hohenau tunnel 2 that were supplied by Rössler (available from the author, also, see Rössler et al., 2007).

PARC is a permanent banding station in Rector, Pennsylvania. In a typical year, more than 11 000 birds of at over 100 species are netted, banded, measured, visually sexed and weighed (https://powdermillarc.org/). Most are migratory individuals netted during spring and fall migration. In a relatively short period of time, this provides large sample sizes of species that are typical victims of collisions.

The PARC tunnel is 8 m long with a cross section of 1.0-m x 1.0 m at the sample end, tapering to 0.45-m x 0.45 m. Construction is plywood and particle board over a steel frame. The tunnel is open at the sample end. 45 cm in front of this opening is a mounting apparatus that holds two, 1.0×0.5 m panels separated by 10 cm: 6.0 mm clear window glass control (supplemental materials A) and a test sample. A section of 24 mm, 70/2 denier/ply mist net (Avinet), shelf cords removed, stretches across this end of the tunnel to prevent birds from hitting glass. At the operator end a light-proof sleeve permits birds to be released in a dark interior, with brightly lit 'exits' viewed at the far end. A video camera is mounted to record flights, and a shelf holds a computer for data recording.

2.2. Bird handling and testing

All personnel handling birds are experienced bird handlers coordinated by a master bander (U.S. Department of the Interior banding permit 08231 04-02-18 A). Birds netted at the banding station are extricated by banding technicians, placed in cloth bags and taken to the station for banding and measuring. Birds to be tested are then brought to the tunnel. A bird is removed from the bag by the tunnel testing technician and evaluated. Any bird that appears stressed is immediately released. Otherwise, the band number is read and recorded and the bird is released into the tunnel through the sleeve in the operator end panel. Birds that do not fly after 30 s are withdrawn and released. Birds are observed and videotaped as they fly down the tunnel towards the light and presumably to exit either via the control or the test panel. Birds completing a flight are scored as flying toward the control sample or test sample (or the side, floor or ceiling). Scores are recorded on a notebook computer or on paper if weather dictates. Each bird is released immediately after one flight by opening a door next to the net.

The 'tunnel score' (Rössler and Zuna-Kratky, 2004) is calculated as (flights to control/total flights*100). We define the 'Threat Factor' (TF) as (flights to test panel/total flights*100). Note on sample size at PARC: at the time of the tests described here, we had not adopted a standard number of flights per sample, and sample sizes are more variable than in subsequent trials, where our standard is 80 competed flights. That standard was developed at the International Bird-Safe Glass Forum, held in Konstanz, Germany, March 30th & 31st, 2011 (Fiedler and Ley, 2013). Based on comparisons, where we have both tunnel scores and data from other sources (Klem and Saenger, 2013, FLAP, 2019) we estimate that a tunnel score of 70 (threat factor = 30) will reduce collisions by at least 50%. This is the minimum recommended by the American Bird Conservancy (Sheppard and Phillips, 2015).

2.3. Tunnel operation

The tunnel is mounted on a pivot and is moved every one to 5 min to keep a constant orientation with the sun directly behind the operator. Timing depends on visual assessment of shadows before each trial. Mirrors at the sides of the tunnel reflect light onto the front surfaces of the glass, and natural light falls on the back surface. Test materials are presented in random order and in equal frequency on the left and right side. At the start of the testing season, trials using two clear panes are run as a control. Equal numbers of flights to left and right indicate that the tunnel itself is not influencing the choice made by the birds. Note that a tunnel score of 50 (±5) thus indicates that a test glass product does not influence flight direction.

2.4. Statistical analysis

We used Chi-square (https://www.socscistatistics.com/tests/chisquare2/Default2.aspx) to determine whether the results of each trial differed from 50/50. A two-tailed Fisher's exact test (https://www.graphpad.com/quickcalcs/contingency1/) was used to evaluate differences in scores between different samples.

2.5. Bird taxa

Birds tested at Hohenau were resident species netted primarily (53%) during July and August (Rössler and Zuna-Kratky, 2004; Rössler, 2005). Tunnel testing at PARC was conducted only during spring and fall migration, and virtually all subjects were migrant passerines (see Appendix A for taxonomic breakdown). Some species, like black-capped chickadees (*Poecila atricapillus*) were not tested because they often cling to interior tunnel walls instead of flying toward the glass. Species that might be small enough or heavy enough to go through the net were not tested.

2.6. Reflectivity and test samples

Reflections are the most serious threat posed by glass (Klem, 2006; Gelb and Delacretaz, 2006, 2009; Sheppard, 2011) as birds are unable to distinguish reflected habitat from real. Glass reflection is a complex issue involving many variables (Glassproperties.com, 2019; Viracon Glass, 2007) Ordinary glass used in home windows has a surface reflectivity of about 8% but because reflection takes place at both surfaces of a pane, a measurement taken perpendicular to the surface will produce a higher value, 12−14. Reflection changes with angle of view, and varies with external lighting conditions and weather. Glass can be created with virtually no reflection, or a mirrorlike surface. In addition, coatings applied to glass surfaces to control penetration of UV, or to manage glare and heat exchange, can be highly reflective. Homeowners often discover an increase in bird collisions after they replace their windows, because most replacement windows have reflective coatings. Much glass in modern commercial structures has one or more coatings.

A standard recommendation for both new construction and remediation of existing glass (Klem, 2006; Sheppard and Phillips, 2015; Canadian Standards Association, 2019) is to apply deterrent materials on the outside surface of the glass, so that they cannot be obscured by reflections. If a deterrent pattern must be installed on an internal surface, it is important that the outside surface have low reflectivity. It does not require testing to conclude that a glass with strong reflections that hides a bird deterrent pattern will be ineffective.

Most of the samples tested for this study were created by applying tape, decals or paint to the outside surface of a single pane of glass, so reflections were not an issue. The exceptions were the insulated glass units (two panes of glass separated by a gas filled space, to control heat), described in sections XXX. The patterns on these samples were created during fabrication by applying ceramic dots or ‘frit’ to the inside surface (surface 2) of the ‘outside’ glass pane. Fritted glass is an alternative method of controlling glare and heat, so highly reflective coatings are not necessary, allowing the patterns to be reliably visible (see section 2.8.2).

2.7. Standard patterns

White adhesive tape (2 cm wide, Certoplast) was applied to 0.6 cm window glass (see Appendix B for all glass specifications) to create reference patterns at Hohenau (Rössler and Zuna-Kratky, 2004; Rössler and Laube, 2008, Rössler, 2005; Rössler et al., 2007). Pattern 10H (2 cm horizontal stripes, 10 cm apart) was tested in 2004, 2005 and 2006; pattern 10V (2 cm vertical stripes, 10 cm apart was tested in 2004 and 2005. The same patterns, made using a roll of the same tape, supplied by Rössler were tested at Powdermill in 2010 and 2011.

2.8. Pattern element size, spacing and surface coverage

2.8.1. Classic square window alert decals (https://windowalert.com/windowalert-products/)

We used 8.9 × 8.9 cm square decals and the same decals cut into 8.9 × 2.2 cm strips. These were applied to the tunnel-facing surface of the glass, in 2 or 3 columns, each using 5-cm edge-to-edge vertical spacing, with two different horizontal spacings: either 10.9 or 6.1 cm.

2.8.2. Insulated, fritted glass

We conducted trials with four insulated fritted glass units donated by Viracon Glass (800 Park Drive, Owatonna MN 55060) with designs from their online catalog (Viracon, 2019). The units are illustrated at http://viracon.com/page/printing; for full performance data Appendix B.

2.8.2.1. Scenario 1•. Silk-screen Color: V901 Dark Gray Viraspan• Silk-screen Pattern: 1/8” horizontal lines alternating with 1/2” spaces, equating to 20% coverage (screen 2256).

2.8.2.2. Scenario 2•. Silk-screen Color: V948 Medium Gray Viraspan • Silk-screen Pattern: 1/8” horizontal lines alternating with 1/2” spaces, equating to 20% coverage (screen 2256).

2.8.2.3. Scenario 3•. Silk-screen Color: V175 High Opacity White • Silk-screen Pattern: 1/8” dots, 1/4” on center equating to 20% coverage (screen 5065).

2.9. UV patterned materials

2.9.1. UV Blast lure enhancer spray (UV Blast) (OG coatings)

UV Blast [Atlas materials testing solutions https://www.atlas-mts.com/], sold as an enhancement for fishing lures, reflects about 14% of ultraviolet wavelengths in the range visible to many birds (Ödeen and Håstad, 2013. In a series of trials, 5-cm vertical stripes (5 coats each) of paint were applied with a hand sprayer at 5-cm edge-to-edge intervals: 1. directly on the outside surface of glass, 2. on a 99% UV absorbing film (Gordon Glass Company www.GordonGlassUSA.com item code FCC24-006) applied to the tunnel-facing surface of glass, and 3. alternating with stripes of the UV absorbing film, on the tunnel-facing surface of the glass. The paint appears transparent from some angles of view and slightly frosted from others.

2.9.2. Prototype UV striped film

Klem (2009, experiment 5) described tests of a prototype film with patterns created by combining UV reflecting and absorbing material. In 2010, we were able to obtain enough of this film (CPFilms, Fieldale, VA.) to create a single sample with 2” vertical stripes alternately UV absorbing and UV reflecting.

3. Results and discussion

3.1. Bird taxa

At Hohenau in 2005, 972 individuals were tested (Rössler, 2005). At PARC in 2010, 1310 individuals were tested. All subjects at PARC were passerines; subjects at Hohenau also included Coraciiformes (0.5%) and Piciformes (2.2%). No species or genera were tested at both sites. Members of 3 families were tested at both facilities: Fringillidae (5% of individuals at Hohenau, 0.1% at PARC), Passeridae (8.5% of individuals at Hohenau and 0.05% at PARC), and Turdidae (0.8% of individuals at Hohenau, 0.05% at PARC).

The four most common species at Hohenau, *Acrocephalus palustris* (207), *Emberiza schoeniclus* (125), *Passer montanus* (83) and *Acrocephalus schoenobaenus* (78), comprised just over 50% of total individuals. The four most common species at PARC, *Setophaga magnolia* (124), *Dumetella carolinensis* (121), *Oreothlypis ruficapilla* (98) and *Zonotrichia albicollis* (97) comprised 34% of total individuals.

3.2. Reference patterns

Table 1a summarizes reference pattern trials at Hohenau and PARC (Rössler and Zuna-Kraty, 2004, Rössler, 2005, Rössler et al., 2007, Rössler and Laube, 2008). Results were consistent for the same pattern across years at both facilities, in spite of differences in species, latitude, and longitude (Table 1b, Fisher's exact test, $p = 1.0$). Notably, while the two patterns cover the same area of the glass, they received very different scores (Table 1c, TF = 6 vs TF = 22, Fisher's exact test, $p < .0001$). It seems likely that tunnel results will apply to passerines in general. Since passerines, especially migrants, have the highest collisions rates with glass (Klem, 1989, 1991), the tunnel is a useful tool for evaluating strategies and materials to deter birds from hitting

Table 1a
Scores for horizontal and vertical white stripe patterns at Hohenau and Powdermill. All stripes are 2.0 cm wide and spaced 10.0 cm apart. All scores are $p \leq 0.01$.

Test site	Pattern	%Pattern coverage	Test year	Total flights	Flights to control	Flights to control	p value
Hohenau	10H	16	2004	88	69	78	<0.01
	10H	16	2005	77	60	78	<0.01
	10H	16	2006	77	60	78	<0.01
	10V	16	2004	87	83	95	<0.01
	10V	16	2005	90	84	93	<0.01
PARC	10H	16	2010	57	45	79	<0.01
	10V	16	2010	39	39	100	<0.01
	10V	16	2011	70	64	91	<0.01

Table 1b
Comparison of combined scores for 10H and 10V scores at Powdermill and Hohenau. Fisher's exact test $p = 1$ for both comparisons.

Test site	Pattern	Total flights	Flights to control	Flights to control	Threat Factor (TF)
	10H				
Hohenau		242	189	78	22
PARC		57	45	78	22
	10V				
Hohenau		177	167	94	6
PARC		109	103	94	6

Table 1c
Comparison of overall 10H score with overall 10V scores. Fisher's exact test $p<.0001$.

10H	299	234	78
10V	286	270	94

Table 2
A summary of scores for four arrangements of decal squares and strips, in either two or three columns, with consistent vertical spacing (2.5 cm) between elements. All scores $p < 0.01$. In three columns, with horizontal spacing = 2.4 cm, (Table 2a) strips and squares produce the same score, TF = 8 (Fisher's exact test, $p = 0.18$) in spite of a twofold difference in area of glass covered. In two columns, however, (Table 2b) horizontal spacing = 4.3 cm, both threat factors are higher (18 for squares vs. 26 for strips, Fisher's exact test, $p = 0.22$). All dimensions and spacing in cm.

Table 2a: Window Alert decals, dimensions (cm) and spacing (cm)

P <0.01 in all cases

Decal dimension	Distribution columns x rows	% Surface coverage	Spacing horizontal	Spacing vertical	Total flights	%flights to control	TF
8.9 x 8.9	3x7	33	2.4	5	96	92	8
8.9 x 2.2	3x13	15	2.4	5	78	92	8
8.9 x 8.9	2x7	22	4.3	5	142	82	18
8.9 x 2.2	2x13	10	4.3	5	74	74	26

Table 2b: Window Alert decals, dimensions (cm) and size (cm)

P <0.01 in all cases

Decal dimension	Distribution columns x rows	% Surface coverage	Spacing horizontal	Spacing vertical	Total flights	%flights to control	TF
8.9 x 8.9	2x7	22	4.3	5	142	82	18
8.9 x 8.9	3x7	33	2.4	5	96	92	8
8.9 x 2.2	2x13	10	4.3	5	74	74	26
8.9 x 2.2	3x13	15	2.4	5	78	92	8

glass. This is important, as jurisdictions in the U.S. and Canada are increasingly requiring or recommending use of bird-friendly materials in new construction (Appendix C).

Rössler et al. (2015), in a review of work at Hohenau in 2004-5, conclude that percentage of the glass surface covered by a pattern is not a good predictor of score, and this is supported by my data. Both 10H and 10 V patterns have coverage of 16%, arranged in parallel 2-cm lines that are spaced 10 cm apart, but birds avoided 10H (TF = 22) significantly less than they avoided 10V (TF = 6). This suggests that the orientation of pattern elements must be considered in pattern design and that spaces may be as important as other elements. Additional information is clearly required: the scores for vertical and horizontal lines spaced 10 cm apart are very different, and do not predict scores for 2-cm parallel white lines spaced 10 cm apart at other orientations. This raises several additional questions: Is pattern detection/avoidance a stepwise or gradual change? In this case, does it depend less on spacing than on how willing species are to fly at an angle?

3.3. *Coverage of glass surface, size, contrast and distribution of pattern elements*

3.3.1. *Window alert decals*

However, squares in three columns have a TF = 8, compared to squares in two columns with TF = 18 (Fisher's exact test, $p = 0.o3$), and strips in three columns have TF = 8, versus TF = 26 for strips in two columns (Fisher's exact test, $p<.0001$). For the same, wider spacing (4.3 cm) the larger elements produce a lower threat factor. This could imply that elements with larger areas are inherently better deterrents or that large element size permits larger spacing.

3.3.2. *Ceramic frit patterns*

Again, (Table 3) coverage does not predict scores for the frit patterns, an array of dots (scenario 3) with 20% coverage scoring no better than random, whereas vertical and horizontal stripes (scenarios 1 and 2) with the same 20% coverage produced scores with TF = 10 and TF = 6, respectively. There is evidence (Boström et al., 2016; Ghim and Hodos, 2006) that humans can discriminate among objects at the same distance (contrast sensitivity) more effectively than birds. I speculate that arrays of closely spaced small dots are more difficult for birds to resolve as obstacles than are lines in these samples and that they may lack a strong enough signal to act as a warning of a barrier ahead, possibly resembling empty sky or fog.

3.4. *UV materials*

Trials with UV materials are summarized in Table 4. Contrast is another way that similar patterns can vary. In these trials increased contrast improved scores. There is a great deal of interest in UV patterns for walls and windows, because humans do not see UV wavelengths, possibly permitting effective collision solutions visible only to birds. It should be kept in mind, however, that 1) there is very little, if any, UV in the early morning or on days with low UV indexes and 2) many bird taxa cannot see UV wavelengths (Håstad and Ödeen, 2013).

4. Conclusions

Birds see the world very differently from humans, (Martin, 2009, 2011, 2012) but to reduce the toll on bird populations from collisions with glass, it is imperative that we understand and quantify birds' reactions to proposed solutions to eliminate use of ineffective options. Tunnel testing has a clear role in evaluating materials intended to deter glass collisions in both new construction and retrofits. Results from tunnel testing have reinforced the concept (Sheppard, 2011; Sheppard and Phillips, 2015) that patterns on glass act as virtual barriers to birds, inducing them to change flight paths. However, there is a need to use the tunnel and other protocols to create more comprehensive models of birds avoiding impact with glass.

There has been some computer-based modeling of bird-glass collisions.Håstad and Ödeen (2014) used retinal data for the blue tit (*Cyanistes caeruleus*), as an example of Ultra Violet sensitive species (UVS), and the Indian peafowl, (*Pavo cristatus*) as

Table 3
Scores for two striped and one dotted fritted glass patterns, each covering 20% of the glass surface.

Pattern	Glass surface covered by pattern (%)	Total flights	Flights to control	Flights % to control	p value	TF
3.2 mm diameter white dots 3.2 mm apart	20	107	63	59	ns	
3.2 mm wide vertical lines 12.8 mm apart	20	42	39	90	<0.1	10
3.2 mm wide horizontal lines 12.8 mm apart	20	35	33	94	<0.1	6

Table 4
Scores for UV materials and UV contrast.

Pattern 5 cm vertical stripes spaced 5 cm apart	Total flights	Flights to control	% flights to control	p value	Threat factor (TF)
UV Blast on glass	82	50	64	ns	
UV Blast on UV absorbing film	65	48	71	<0.01	29
UV Blast alternating with film	29	25	86	<0.01	14
Prototype UV reflecting film	64	53	83	<.01	17

an example of Violet Sensitive (VS) species. They collected photospectrometrical data to represent four scenarios encountered by birds, including reflections and views through glass of different habitats. They modeled window markings as UV filters removing 25, 50 and 100% of UV wavelengths and calculated whether or not the markings would be detectable (not only visible, but different enough from the background to stand out) under different conditions.

Stevens (Stevens et al., 2007; Stevens, 2011; Troscianko and Stevens, 2012) has developed a model of avian vision based on large format digital photography, and Cassey et al. (2008) has developed 'biologically realistic sensory models' to relate variability of behavioral responses to variation in colors and other pattern elements of egg shells. This type of model could be used to quantify the extent to which the reflective surface of a glass with a bird-friendly pattern reduces the visibility of the pattern from different angles and at different times of day.

Endler and Mielke (2005) describe patterns and their backgrounds as 'mosaic of patches that vary in colour, brightness, size, shape and position' and points out the need to determine the relevance of particular patterns to birds, given the differences between avian and human vision. While humans tend to focus on the patches that create patterns, it is the spaces created by those patches that seem to be most important to birds, reinforcing the finding that increasing coverage of glass surfaces does not correlate with effectiveness of flight deterrence. The tunnel test is a way to evaluate particular patterns, but also allows us to tease out the impact of particular aspects of patterns on reaction of birds to the whole.

As awareness increases of the scope of bird mortality from glass, the use of such materials is increasingly being required and the ability to rate materials intended to deter collisions is essential. The tunnel test, combined with other information on close range navigation, can provide basic information but also information that could lead to more sophisticated models, incorporating more variables about glass and patterns on glass, as well as characteristics of environments where glass will be used. Fortunately, two and three dimensional patterns can be translated into materials like fritted glass, sunshades and louvers, elements of sustainable design that help control temperature and light in buildings. Tunnel test scores are one way to bridge the gap from conservation need to action.

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Appendices A. Supplementary data

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