Migratory Bird-Window Collisions: Understanding Physiology, Risk Factors, and Evaluating Mitigation Measures

Ryan Zhang

Abstract

Migratory birds, totaling ~25% of all bird species, fill many ecological roles and are vital for global ecosystems. Urban areas interrupt migrant flyways, forcing birds to fly through unfamiliar environments. This paper reviews the reasons and risk factors behind bird-window collisions and evaluates mitigation strategies.

Birds focus their visual attention on searching for foraging opportunities and predators instead of obstacle detection. This leads to an overload of their visual processing systems in the unfamiliar urban environment, causing 365 to 988 million annual window collisions in the US alone. Larger windows with higher reflectivity are dangerous as they are harder to detect and reflect more of the surrounding environment. Various window markings have been developed to allow birds to detect obstacles; the most effective are vertical stripes (94% risk reduction) and large, round dots (100% risk reduction). Most diurnal migrants can see UV light, which allows effective markings to reflect and absorb UV light, which is invisible to humans. The most effective markings are the 100% absorbent film (100% risk reduction) and any measures to increase the contrast between UV reflectance and absorbance across the same pane (71-91% risk reduction).

"In a Nutshell"

- Migratory birds play vital ecological roles but are at high risk of fatal collisions with windows in urban areas.
- Birds, especially migrants, collide with windows, killing hundreds of millions each year.
- Homeowners and urban planners should incorporate opaque vertical stripes or dots on windows or employ a commercial UV film to create contrast in the birds' vision.
- Further in-field research is needed to evaluate the efficacy of all markings in realistic scenarios, though collision-prevention actions must be taken in the absence of concrete evidence.

Table of Contents

Introduction

One in five birds is migratory, although bird migration is primarily a phenomenon of the Northern Hemisphere (Kirby et al., 2008). Birds move north during spring to catch the burgeoning insects, start their summer breeding season, and move south in the winter to escape the harsh cold of the north (Kirby et al., 2008).

In this paper, I review the impacts of window collisions on migratory birds and evaluate potential mitigation strategies.

Ecological Importance: Functional Role

Birds play various roles in the ecosystem as predators, scavengers, pollinators, and seed dispersers (Whelan et al., 2008; Jones et al., 1994) and are an essential conservation target.

Seed Dispersal

Birds, especially migrants, hold an important role in seed dispersal, as they can carry seeds over long distances (González-Varo et al., 2021; Heleno et al., 2011; Viana et al., 2016). Frugivorous birds, including specialized seed dispersers and seed predators, eat whole fruits and disperse their seeds through droppings (Heleno et al., 2011). Viana et al. (2016) found that roughly 1.5% of migratory birds found on Alegranza, an island in the Canary Archipelago and a convergence of the East Atlantic and Adriatic flyways (Figure 1), carried seeds. The billions of migratory birds between Europe and Sub-Saharan Africa suggest millions of seeds being dispersed across locations (Viana et al., 2016).

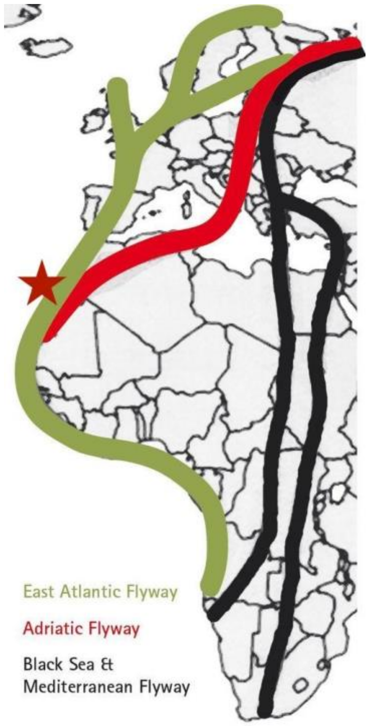

Figure 1: Map of East Atlantic, Adriatic, and Mediterranean/Black Sea Flyways (Ferger, 2022). The star shape represents the location of the Canary Islands.

Migratory birds' seed dispersal abilities have various additional effects, including expanding forest fragments by dispersing seeds near the forest edges and counteract climate change's impact on flora by dispersing seeds to cooler latitudes while migrating northward (González-Varo et al., 2021). However, the exact effects require further quantification.

Predation/Scavenging

Birds are effective predators who prey on herbivorous insects, weeds, and rodents (Whelan et al., 2008). Woodpeckers kill pests like bark beetles, reducing bark and leaf damage in flora like bilberry (reduced larvae density by 63%), spruce, and sapling white oaks (Reviewed by Whelan et al., 2008). While studies show mixed results of raptors' effects on rodent populations, birds consume high amounts of weeds in agricultural landscapes like cereal fields (Reviewed by Whelan et al., 2008).

Birds also reduce disease transmission through scavenging. For example, vultures' scavenging in South Asia is estimated to prevent up to $2.4 billion of human health costs annually (Mainwaring, 2017).

Pollination

Birds pollinate approximately 5.4% of 940 cultivated plant species and ~ 5% (or 10% for islands) of regional fauna (Reviewed by Whelan et al., 2008). While birds pollinate quantitatively less than insects, certain hummingbirds can pollinate in harsh weather (Cruden, 1972), and all pollinating birds have higher effectiveness due to carrying pollen on their feathers (Bees deposited only 25% of pollen compared to birds; the success of the flower to transition to fruit is ten times greater in bird-pollinated plants) (Ramsey, 1988).

Migrant Flyways and Stopover Sites

Flyways

Migratory birds have set flyways, following the same path in each year's migration (Kranstauber et al., 2015). These flyways evolved to optimize flight efficiency and survival using wind direction, air pressure (Figure 2), and other factors, reducing average travel time by 26.5% compared to a direct line of flight to their destination (Kranstauber et al., 2015). Interestingly, flight paths from north to south tend to be more easterly than the returning paths, resulting in loop migrations due to a combination of multiple reasons, an example of route optimization (Figure 2) (Kranstauber et al., 2015).

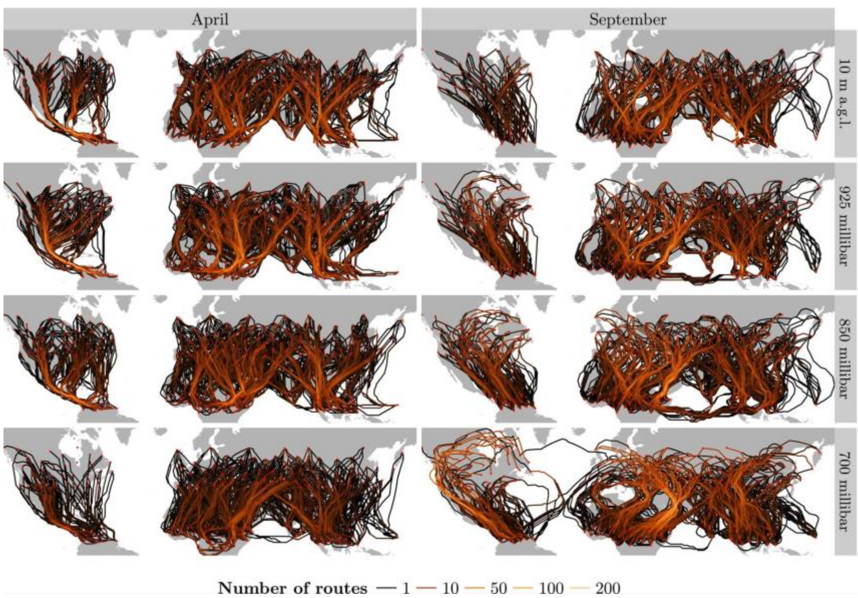

Figure 2: Map of global bird migration routes in the spring and autumn migration seasons. The rows show flyways 10 m above ground and at different atmospheric pressures: 925, 850 and 700 millibars. This represents flyways at different altitudes, with the three millibar values representing 779, 1502 and 3130 m above sea level. Lighter lines represent more concentration of birds (Kranstauber et al., 2015).

Stopover sites

Stopover sites are an interruption of migratory endurance flight to minimize fitness costs (Schmaljohann et al., 2022). Some migratory birds may stop for longer periods at each stop and fly nonstop for longer (Staging sites). In contrast, others take daily stops (Stopover sites), depending on individual differences between species (Figure 3) (Schmaljohann et al., 2022). Land areas under each flyway must always remain safe for migrants' landing, as the birds may fly low and make stopovers at any point.

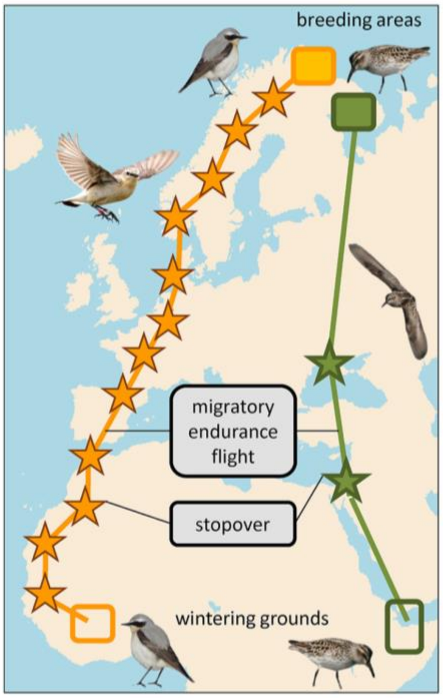

Figure 3: Potential migratory endurance flights (solid line) and stopover sites (star) for a Wader (Limicola falcinellus Pontoppidan; Green) and a songbird (Oenanthe oenanthe Linnaeus; Yellow) (Schmaljohann et al., 2022)

Urban Areas: Impact on Migrant Birds

Urban Areas Along Flyways

Areas with the highest urban density in North America tend to lie on the paths of migratory birds (La Sorte et al., 2017). La Sorte et al. (2017) mapped the distribution of 40 nocturnally migrating species on the east coast of North America during migration, finding that species richness is not impacted by how dense an urban area is (La Sorte et al., 2017) (Figure 4). This suggests that migrants have a fixed travel pattern, which cannot be changed to avoid cities (Figure 7) (Kranstauber et al., 2015).

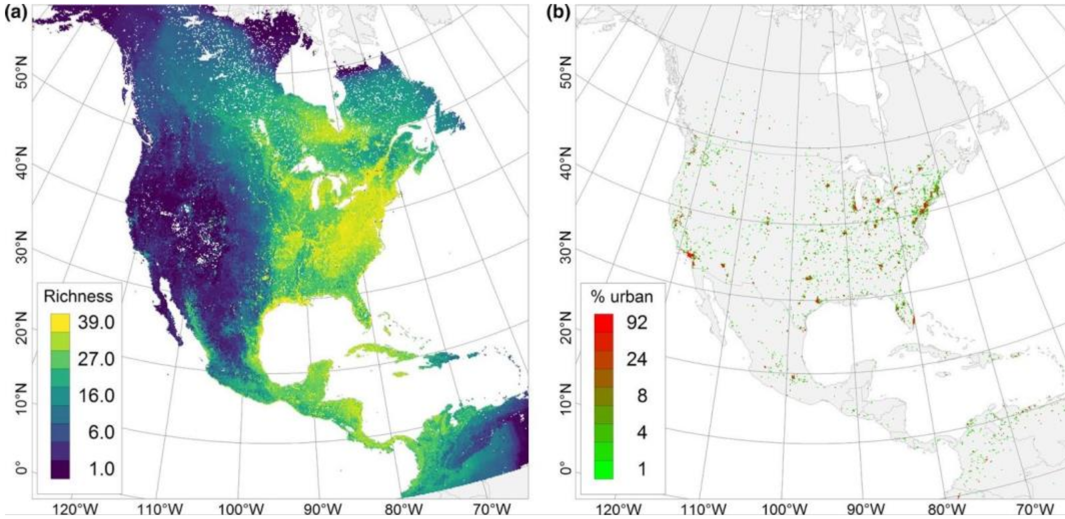

Figure 4: Maps displaying species richness during migration seasons through an analysis of 40 nocturnally migrating species (a) and percent of land summarized as "urban" in the 3.3 x 3.3km grid analysis (b) (La Sorte et al., 2017).

Danger of Urban Areas – Window Collisions

Window Collisions: Scale and Severity

Urban areas pose significant threats to the conservation of migratory species. Window collisions are the largest anthropogenic source of bird mortality globally (Klem et al., 2004; Loss et al., 2014). Loss et al. (2014) estimated that the annual bird-window collision mortality ranges from 365 to 988 million individuals in the US (Loss et al., 2014). The collision fatalities during the autumn migration season account for 0.5-5% of the US bird population (Cusa et al., 2015). The immediate fatality rate of birds after the collision is 38% (Bayne et al., 2012). These mortality counts are likely underestimates, as Powers et al. (2021) estimates that two observers per day could collectively miss 27% of all carcasses in suburban areas.

Bird mortality rates vary depending on the type of building they collide with. Loss et al. (2014) analyzed the mortality rate of all recorded collisions based on different building types (Table 1). Since the collision rate is higher for lower buildings but mortality per building is higher for taller buildings, each building type should be equally prioritized with prevention methods.

Building Type	Residential (1-3 Stories) (Loss et al., 2014; Bayne et al., 2012; Bracey et al., 2016)	Low-Rise (4-11 Stories) (Loss et al., 2014)	High-Rise (>11 Stories) (Loss et al., 2014)
% of Collisions	44%	56%	>1%
Mortality per Building	1.7 - 16	21.7	24.3

Table 1: (Row 2) Percent of collisions in Loss et al. (2014)'s study for each building type. (Row 3) Mortality per building from Loss et al. (2014), Bayne et al. (2012), and Bracey et al. (2016).

Migratory Birds Are Especially Vulnerable

Mortality and collision rates in urban areas are disproportionately high for migrant birds (Sabo et al., 2016). Out of >92,000 window-collision fatality records, the five most vulnerable species were all migrants, and the three most vulnerable taxa were long-distance migrants (Loss et al., 2014). Migrants are nine times more likely to die from window strikes than residents, with 90% of all annual mortalities occurring during the spring and autumn migration seasons (Borden et al., 2010), despite less abundant long-distance migrants like the Red-eyed Vireo and Eastern Wood-Pewee having significantly higher collision rates than more abundant residents like the House Sparrow or American Goldfinch (Hager & Craig, 2014). This suggests that the abnormal collision rate of migrants must be due to a physiological or behavioral difference.

Physiological Explanation of High Migrant Collision Risk

We must understand the physiology of bird sight and its interactions with the anthropogenic environment to understand why migrant birds are especially susceptible to collisions.

Birds in flight focus their attention and highest-resolution vision in their lateral fields on foraging opportunities, prey, and predators (Martin, 2017; Martin, 2011). Most birds use frontal or peripheral vision, which has a lower resolution than the lateral fields, to focus on obstacle detection (Martin, 2011). Birds have evolved to avoid stationary, non-reflective objects like mountains and trees but not unfamiliar materials like glass without much effort (Martin, 2011). A low-flying migrant searching for a stopover site, who is not focused on obstacle detection, moves fast through the unfamiliar urban environment. Unless specific signals warn birds of the impending collision, this overloads their visual processing system, leading to a collision before they can effectively alter their course (Martin, 2011; Gibson, 1986).

Further study is needed to determine whether migrant birds can adapt to detecting windows after gaining familiarity with urban areas.

Window & Environment Characteristics

The characteristics of the window and its environment have significant impacts, both positive and negative, on collision risk. These characteristics include window size and reflectivity, seasonality, and vegetation surrounding windows (Klem et al., 2009; Kahle et al., 2016; Cusa et al., 2015).

Window size

Panel size directly and positively correlates with bird collision risk (Kahle et al., 2016). Kahle et al. (2016) analyzed bird strikes at a single building for over five years and found that 91.11% of all collisions occurred at large panels (wider than 0.5m) despite only covering 48.03% of the total window area. When isolating for all environmental factors, large-panelled glass saw ten times more fatal strikes than smaller windows (Kahle et al., 2016). In addition, Klem et al. (2009) conducted an observational study on Manhattan Island with over 500 recorded collisions. They found that a 10% increase in the proportion of the glass building façade led to a 19% and 32% increase in risk in autumn and spring, respectively. Cusa et al. (2015) found a similar trend by analyzing 7,968 collisions in Toronto, Canada.

Window reflectivity

The reflectivity of glass panels makes it difficult for birds to recognize distance and worsens when migrant birds become distracted by the unfamiliar environment (Klem et al., 2009). Window reflectivity in itself holds no directly significant correlation with collision risk. However, the environment around the building being reflected on panels strongly correlates to collision risk, as shown in Klem et al. (2009)'s Manhattan Island observational study. They showed that a 10% increase in tree height near windows resulted in a 19% and 22% increase in collision risk in autumn and spring. The reflection of vegetation in windows significantly increased the likelihood of collision.

Prevention Methods: Window Alterations

Opaque Markings

To mitigate the imbalance in visual processing speed and unfamiliar obstacles, researchers are designing solutions for windows that clearly indicate the presence of an unfamiliar obstacle to the birds, similar to the hazard warnings on highways (Martin, 2011).

Opaque markings are the most tested prevention method for bird-window collisions.

Stripe-Shaped Markings

Stripes are the first type of window marking to prevent collisions. In addition, orientation was an important factor, as vertical stripes (Figure 5b) were significantly more effective than horizontal stripes (Figure 5d) of the same width (Rössler et al., 2015; Klem & Saenger, 2013; Sheppard, 2019). This may be the result of birds' unwillingness to fly at an angle between the vertical stripes, while they can fly easily between horizontal stripes, but further research is needed (Sheppard, 2019). 2cm wide vertical stripes with 10cm in between are most optimal, with a 94% risk reduction (Rössler et al., 2015).

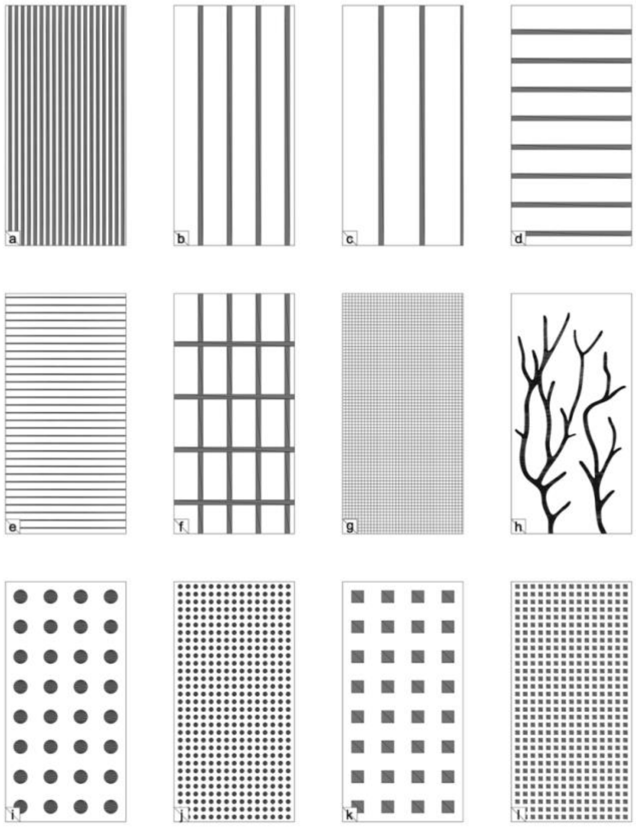

Figure 5: List of example markings tested by Rössler et al. (2015)

Dot-Shaped Markings

Dot-shaped markings have varying efficacy depending on size. Sheppard (2019) and Rössler et al. (2015) both found no significant correlation between a fine grid (Figure 5j; covering of 3.2mm diameter white dots 3.2mm apart) and collision risk. Slightly larger dots that are 1.8cm in diameter and 3.2cm apart (covering 25% of the window) resulted in a 100% reduction in the number of collisions (Rössler et al., 2015). Interestingly, dots were significantly more effective than squares or stripes (Rössler et al., 2015). Feather Friendly (Figure 6), a commercial product utilizing a grid of white dots (1cm diameter) on windows, leads to a significant 95% reduction in collision risk (Groot et al., 2022), further supporting the efficacy of dot-shaped markings.

Figure 6: Example of Feather Friendly adhesive markings on windows at the Science Complex at the Alaksen National Wildlife Area, Delta, British Columbia (Groot et al., 2022).

Flaws of the Tunnel Testing Apparatus

Most research on the efficacy of opaque markings is done using the “tunnel testing” method (Rössler et al., 2015; Sabo et al., 2016). Birds are released into a dark tunnel with the only source of light at the end (Figure 7). As birds fly towards the light source, the tunnel is split into two 0.5 x 0.5m panes, one of which is marked and the other unmarked (Figure 7). The birds' choices of which pane to fly towards are recorded.

These are not realistic parameters, and they fail to represent the environment as accurately as a field experiment can. Though tunnel testing is effective at predicting which shapes birds react to most strongly in the absence of light, this method does not take into account the possible interactions between light and the material or color of the marking, including any reflective qualities of the glass and markings. In addition, the use of one active light source as the only point of concentration for the bird lacks the overloading of their visual processing systems present in situ. Lastly, the tunnel's panes are both only 0.5 x 1m in size. Panes smaller than 0.5m in width are classified as small panes by Kahle et al. (2016), with these panes having ten times fewer fatal strikes than larger panes. The efficacy of window markings on larger panes must be tested, as their effect may be different across a larger surface area. Further observational research is needed for a thorough analysis, though it will be challenging to control a variety of environmental factors (Rössler et al., 2015), and policy decisions must be made in the absence of concrete evidence.

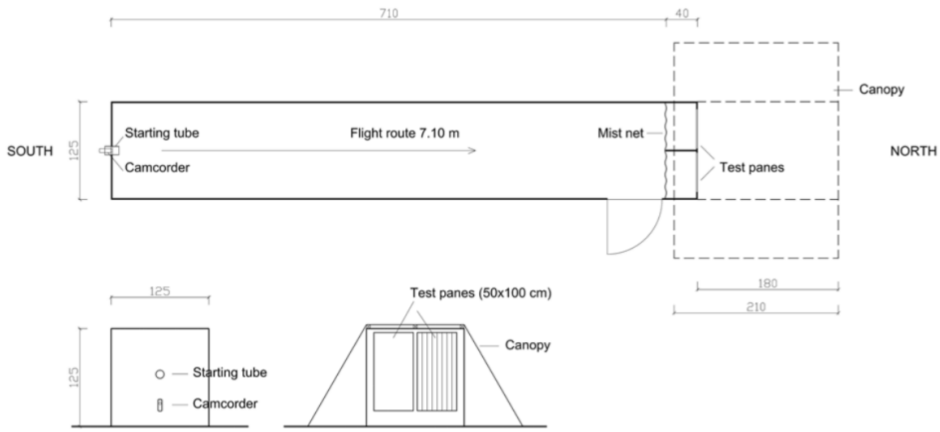

Figure 7: Diagram of tunnel testing apparatus (Rössler et al., 2015)

UV markings

Birds possess two different types of visual systems: Ultraviolet Sight (UVS) and Violet Sight (VS). Birds with UVS can see ultraviolet light, which is beyond the range of human vision. This allows them to perceive colors of lower frequency than those with VS, which is similar to human vision and limited to the higher end of the spectrum. Because of this extended range, UV filters are effective for birds with Ultraviolet Sight (UVS) but have no impact on birds with Violet Sight (VS, e.g. human vision).

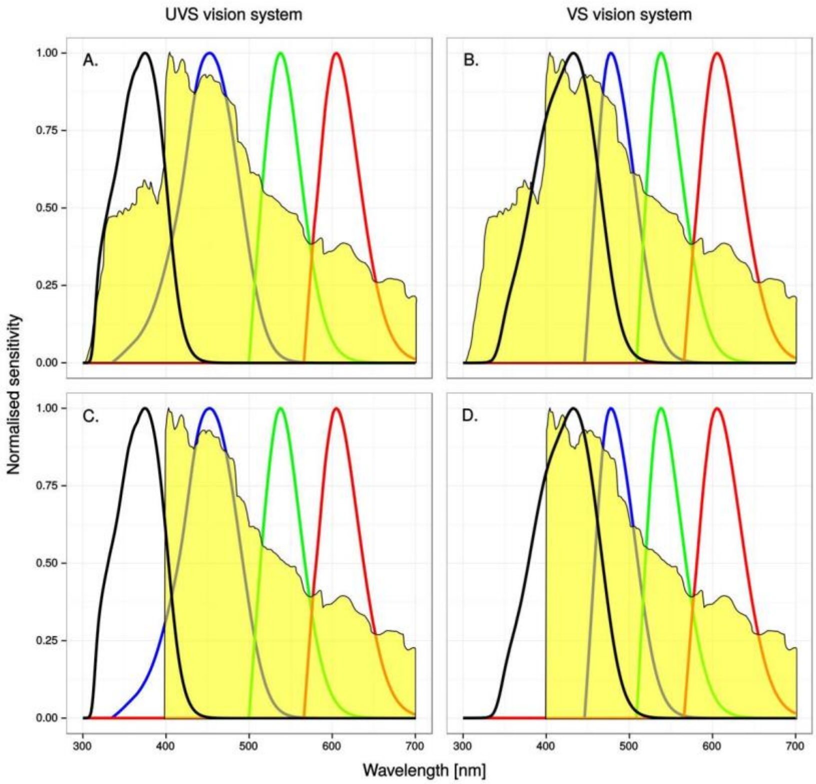

Figure 8: Spectroradiogram (Yellow shading) of clear sky unaltered (A & B) and modified (C & D) overlapping with visual cones (four curves) of UVS birds (A & C) and VS birds (B & D) (Håstad & Ödeen, 2014). This shows how birds with UVS can see changes in UV light.

The purpose of UV markings is to shift the spectrum of wavelengths of the high-rise windows' reflections to differ from the spectrum of the unaltered, clear sky (Håstad & Ödeen, 2014). A majority of birds, including most diurnal migrants, have the capability of UVS, but UV markings are not visible to birds with VS (Figure 9) (Håstad & Ödeen, 2014).

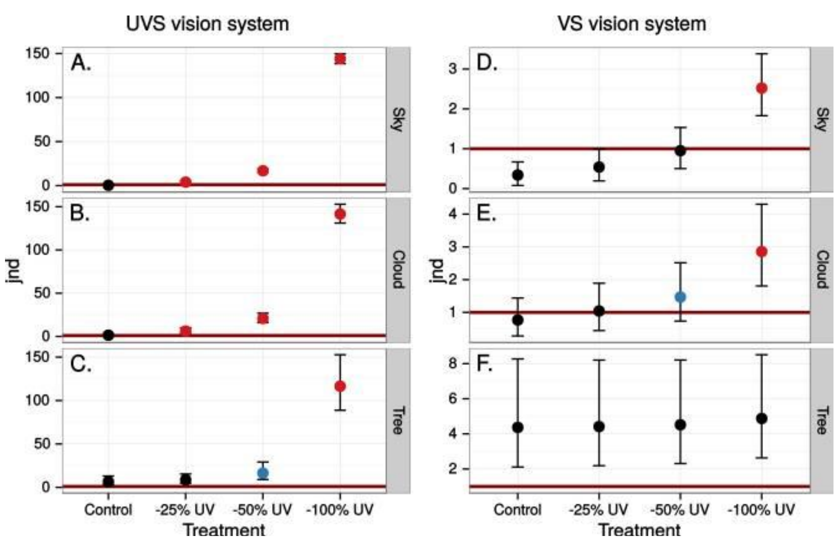

Figure 9: Just Noticeable Difference (jnd) in random patches of the window and background with four intervals of UV reduction treatment (control, -25%, -50%, -100%) between vision systems UVS and VS. jnd is a unit used to quantify the smallest

detectable difference in color or brightness between two visual stimuli. Jnd values below one are not visible to the modelled eye, and higher values are more visible (Håstad & Ödeen, 2014).

UV filters can be sorted into two types: UV absorbent and UV reflectant. UV absorbent film is largely opaque on the outside and clear on the inside. UV reflectant film maintains the appearance of the window on the outside and appears neutral from the inside. Despite UV light typically representing signals of attraction behavior, sexual selection, and finding food (Klem, 2009b), the UV reflectant film is hypothesized to act as a mechanism to signal threats for birds with UV vision alerting the bird that there is an unfamiliar object present and allowing the bird's visual processing to "catch up" to the speed of flight. Klem (2009b) supports the claim that commercial UV reflecting films are only somewhat effective, with evidence from six field experiments that tested the effectiveness of a variety of commercially available UV films and one-way films. Through a spectrophotometer analysis, they found that while a film must reflect 20–40% of UV from 300–400 nm to be effective (Klem & Saenger, 2013) and 50% be clearly visible (Håstad & Ödeen, 2014), all commercially available UV films only achieved a maximum of 13% UV-reflectance (Klem, 2009b).

In addition, Klem (2009b) showed that a complete 100% UV absorbent one-way film appearing as entirely black or white from the outside resulted in only 1 of 77 total collisions in that experiment (out of 3 windows). However, vertical markings 2.5cm in width and 5cm apart with the same material received 35% of all strikes (out of 3 windows) with no significant difference between the number of impacts on striped and unstriped areas (Klem, 2009b).

UV-reflective patterns on plain glass are not an effective mitigation method, as a full coverage of UV reflectant spray (14%) over the window is insignificant (Sheppard, 2019). Groot et al. (2022)'s analysis in Delta, British Columbia, found that ORNILUX, a film with areas of web-like UV reflectant patterns over plain glass significantly reduced collision risk by 71% from 2013 and 2015 but was not significant from 2016 to 2018. Klem and Saenger (2013) found that the ORNILUX had an even lower efficacy in reducing risk.

Creating contrast between UV reflectance and absorbance across the same panel is very effective at reducing collision risk. With 37 standard tunnel tests, Swaddle et al. (2020) show that the commercial film BirdShades, which makes vertical stripes contrasting in UV reflectance, can reduce collision risk by 91% and 75% in two short to medium-distance migrants. Supporting this hypothesis, Sheppard (2019) found that UV reflectant spray (14%) over the top of a UV absorbent film led to a 71% risk reduction, and UV spray alternating with UV absorbent film led to an 86% effectiveness. This shows a possible relationship between contrast and risk reduction.

Comprehensive studies are needed to evaluate the hypothesis of contrast, but in the absence of concrete studies, immediate action must be taken.

Recommendations/Conclusion

The most effective solutions with on-window markings and films depend on the building's context and design. A few effective options are available, and policymakers should enforce the usage of these methods of prevention on windows. For opaque markings visible to the human eye, 2mm wide vertical black strips, 10cm apart, and dots that are 1.8cm in diameter and 3.2cm apart are effective options (Rössler et al., 2015; Klem & Saenger, 2013; Sheppard, 2019).

UV films are only effective for birds with UV sight, which most birds have, except for nocturnal birds like owls. The two types of UV film – UV absorbent and UV reflectant – can be used in conjunction in varying situations. Reflectant films must reflect at least 20-40% of UV light to be somewhat visible to birds; all commercial reflectant film products should meet this criterion to be used by residences or low/high-rise buildings (Klem & Saenger, 2013).

Some commercially available UV reflectant films like the ORNILUX are relatively ineffective (Groot et al., 2022; Klem & Saenger, 2013), while others like Birdshades, which creates more contrast, are proven to be highly effective in at least two migrant species (Swaddle et al., 2020). Absorbent films are very effective at blocking the reflection of almost all light from the outside and maintaining a neutral look on the inside (Klem, 2009b). Measures to increase contrast, like reflectant patterns (vertical stripes and dots, as previously mentioned) sprayed on top of an absorbent film (Sheppard, 2019), are very effective in preventing collisions, and contrast should be the general framework for evaluating the efficacy of commercial UV films without thorough study. However, it is important to note that birds hold cognitive emphasis on their non-UV cones in obstacle detection, suggesting that, in practice, opaque markings may be more effective than UV markings (Campenhausen & Kirschfeld, 1998).

Further research should focus on evaluating the effects of high-contrast UV markings and dots/vertical stripes' efficacy in observational studies. It should also aim to create a concrete list of which birds possess some form of UVS and track migrant birds' behavior through urban areas.

Bibliography

Amano, T., & Yamaura, Y. (2007). Ecological and life-history traits related to range contractions among breeding birds in Japan. *Biological Conservation*, *137*(2), 271–282. https://doi.org/10.1016/j.biocon.2007.02.010

Bayne, E. M., Scobie, C. A., & Rawson-Clark, M. (2012). Factors influencing the annual risk of bird-window collisions at residential structures in Alberta, Canada. *Wildlife Research*, *39*(7), 583–592. https://doi.org/10.1071/WR11179

Borden, W. C., Lockhart, O. M., Jones, A. W., & Lyons, M. S. (2010). Seasonal, Taxonomic, and Local Habitat Components of Bird-window Collisions on an Urban University Campus in Cleveland, OH. *The Ohio Journal of Science*, *110*(3), 44–52.

Bracey, A. M., Etterson, M. A., Niemi, G. J., & Green, R. F. (2016). Variation in bird-window collision mortality and scavenging rates within an urban landscape. *The Wilson Journal of Ornithology*, *128*(2), 355–367. https://doi.org/10.1676/wils-128-02-355-367.1

Campenhausen, M., & Kirschfeld, K. (1998). Spectral sensitivity of the accessory optic system of the pigeon. *Journal of Comparative Physiology A*, *183*(1), 1–6. https://doi.org/10.1007/s003590050229

Cruden, R. W. (1972). Pollinators in High-Elevation Ecosystems: Relative Effectiveness of Birds and Bees. *Science*, *176*(4042), 1439–1440. https://doi.org/10.1126/science.176.4042.1439

Cusa, M., Jackson, D. A., & Mesure, M. (2015). Window collisions by migratory bird species: Urban geographical patterns and habitat associations. *Urban Ecosystems*, *18*(4), 1427–1446. https://doi.org/10.1007/s11252-015-0459-3

Ferger, S. (2022). *Working together for Europe's migratory birds*. https://www.euronatur.org/fileadmin/_processed_/2/d/csm_European-African-Flyways_6edd1fb883.jpg

González-Varo, J. P., Rumeu, B., Albrecht, J., Arroyo, J. M., Bueno, R. S., Burgos, T., da Silva, L. P., Escribano-Ávila, G., Farwig, N., García, D., Heleno, R. H., Illera, J. C., Jordano, P., Kurek, P., Simmons, B. I., Virgós, E., Sutherland, W. J., & Traveset, A. (2021). Limited potential for bird migration to disperse plants to cooler latitudes. *Nature*, *595*(7865), Article 7865. https://doi.org/10.1038/s41586-021-03665-2

Groot, K. L. D., Wilson, A. G., McKibbin, R., Hudson, S. A., Dohms, K. M., Norris, A. R., Huang, A. C., Whitehorne, I. B. J., Fort, K. T., Roy, C., Bourque, J., & Wilson, S. (2022). Bird protection treatments reduce bird-window collision risk at low-rise buildings within a Pacific coastal protected area. *PeerJ*, *10*, e13142. https://doi.org/10.7717/peerj.13142

Hager, S., & Craig, M. (2014). Bird-window collisions in the summer breeding season. *PeerJ*, *2*. https://doi.org/10.7717/peerj.460

Hartz, S. M., Pinheiro, G. C., Mendonça-Lima, A. D., & Duarte, L. D. S. (2012). The Potential Role of Migratory Birds in the Expansion of Araucaria Forest. *Natureza & Conservação*, *10*(1), 52–56. https://doi.org/10.4322/natcon.2012.009

Håstad, O., & Ödeen, A. (2014). A vision physiological estimation of ultraviolet window marking visibility to birds. *PeerJ*, *2*, e621. https://doi.org/10.7717/peerj.621

Heleno, R. H., Ross, G., Everard, A., Memmott, J., & Ramos, J. A. (2011). The role of avian 'seed predators' as seed dispersers. *Ibis*, *153*(1), 199–203. https://doi.org/10.1111/j.1474-919X.2010.01088.x

Jones, C. G., Lawton, J. H., & Shachak, M. (1994). Organisms as Ecosystem Engineers. *Oikos*, *69*(3), 373. https://doi.org/10.2307/3545850

Kahle, L. Q., Flannery, M. E., & Dumbacher, J. P. (2016). Bird-Window Collisions at a West-Coast Urban Park Museum: Analyses of Bird Biology and Window Attributes from Golden Gate Park, San Francisco. *PLOS ONE*, *11*(1), e0144600. https://doi.org/10.1371/journal.pone.0144600

Kirby, J. S., Stattersfield, A. J., Butchart, S. H. M., Evans, M. I., Grimmett, R. F. A., Jones, V. R., O'Sullivan, J., Tucker, G. M., & Newton, I. (2008). Key conservation issues for migratory land- and waterbird species on the world's major flyways. *Bird Conservation International*, *18*(S1), S49–S73. https://doi.org/10.1017/S0959270908000439

Klem, D. (2009). Preventing Bird–Window Collisions. *The Wilson Journal of Ornithology*, *121*(2), 314–321. https://doi.org/10.1676/08-118.1

Klem, D., Farmer, C. J., Delacretaz, N., Gelb, Y., & Saenger, P. G. (2009). Architectural and Landscape Risk Factors Associated with Bird–glass Collisions in an Urban Environment. *The Wilson Journal of Ornithology*, *121*(1), 126–134. https://doi.org/10.1676/08-068.1

Klem, D., & Saenger, P. G. (2013). Evaluating the Effectiveness of Select Visual Signals to Prevent Bird-window Collisions. *The Wilson Journal of Ornithology*, *125*(2), 406–411. https://doi.org/10.1676/12-106.1

Kranstauber, B., Weinzierl, R., Wikelski, M., & Safi, K. (2015). Global aerial flyways allow efficient travelling. *Ecology Letters*, *18*(12), 1338–1345. https://doi.org/10.1111/ele.12528

La Sorte, F. A., Fink, D., Buler, J. J., Farnsworth, A., & Cabrera-Cruz, S. A. (2017). Seasonal associations with urban light pollution for nocturnally migrating bird populations. *Global Change Biology*, *23*(11), 4609–4619. https://doi.org/10.1111/gcb.13792

Loss, S. R., Will, T., Loss, S. S., & Marra, P. P. (2014). Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability. *The Condor*, *116*(1), 8–23. https://doi.org/10.1650/CONDOR-13-090.1

Mainwaring, M. C. (2017). Why Birds Matter: Avian Ecological Function and Ecosystem Services. *The Condor*, *119*(2), 354–355. https://doi.org/10.1650/CONDOR-17-9.1

Martin, G. R. (2011). Understanding bird collisions with man-made objects: A sensory ecology approach. *Ibis*, *153*(2), 239–254. https://doi.org/10.1111/j.1474-919X.2011.01117.x

Martin, G. R. (2017). What Drives Bird Vision? Bill Control and Predator Detection Overshadow Flight. *Frontiers in Neuroscience*, *11*. https://doi.org/10.3389/fnins.2017.00619

Powers, K. E., Burroughs, L. A., Harris, N. I., & Harris, R. C. (2021). Biases in Bird-Window Collisions: A Focus on Scavengers and Detection Rates by Observers. *Southeastern Naturalist*, *20*(2). https://doi.org/10.1656/058.020.0207

Rajchard, J. (2009). Ultraviolet (UV) light perception by birds: A review. *Veterinární Medicína*, *54*(8), 351–359. https://doi.org/10.17221/110/2009-VETMED

Ramsey, M. W. (1988). Differences in pollinator effectiveness of birds and insects visiting Banksia menziesii (Proteaceae). *Oecologia*, *76*(1), 119–124. https://doi.org/10.1007/BF00379609

Rössler, M., Nemeth, E., & Bruckner, A. (2015). Glass pane markings to prevent bird-window collisions: Less can be more. *Biologia*, *70*(4), 535–541. https://doi.org/10.1515/biolog-2015-0057

Sabo, A. M., Hagemeyer, N. D. G., Lahey, A. S., & Walters, E. L. (2016). Local avian density influences risk of mortality from window strikes. *PeerJ*, *4*, e2170. https://doi.org/10.7717/peerj.2170

Schmaljohann, H., Eikenaar, C., & Sapir, N. (2022). Understanding the ecological and evolutionary function of stopover in migrating birds. *Biological Reviews*, *97*(4), 1231–1252. https://doi.org/10.1111/brv.12839

Sheppard, C. D. (2019). Evaluating the relative effectiveness of patterns on glass as deterrents of bird collisions with glass. *Global Ecology and Conservation*, *20*, e00795. https://doi.org/10.1016/j.gecco.2019.e00795

Swaddle, J. P., Emerson, L. C., Thady, R. G., & Boycott, T. J. (2020). Ultraviolet-reflective film applied to windows reduces the likelihood of collisions for two species of songbird. *PeerJ*, *8*, e9926. https://doi.org/10.7717/peerj.9926

Viana, D. S., Gangoso, L., Bouten, W., & Figuerola, J. (2016). Overseas seed dispersal by migratory birds. *Proceedings of the Royal Society B: Biological Sciences*, *283*(1822), 20152406. https://doi.org/10.1098/rspb.2015.2406

Whelan, C. J., Wenny, D. G., & Marquis, R. J. (2008). Ecosystem Services Provided by Birds. *Annals of the New York Academy of Sciences*, *1134*(1), 25–60. https://doi.org/10.1196/annals.1439.003