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The influence of artificial light at night and polarized light on bird-building collisions

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ABSTRACT

Collisions with buildings annually kill up to 1 billion birds in the United States. Bird-building collisions primarily occur at glass surfaces: birds often fail to perceive glass as a barrier and appear to be attracted to artificial light emitted from windows. However, some aspects of avian vision are poorly understood, including how bird responses to different types of light influence building collisions. Some evidence suggests birds can detect polarized light, which may serve as a cue to assist with migration orientation and/or detect water bodies. Dark, reflective surfaces, including glass, reflect high degrees of polarized light, causing polarized light pollution (PLP). However, no studies have analyzed the relationship between bird collisions and PLP reflected from buildings. Additionally, while artificial light at night (ALAN) is frequently implicated as a major factor influencing bird-building collisions, few studies have analyzed this relationship. We investigated both types of light pollution—PLP and ALAN—and their association with bird collisions at 48 façades of 13 buildings in Minneapolis, Minnesota, USA. We found that the area of glass emitting ALAN was the most important factor influencing collisions, and that this effect of ALAN was independent of overall glass area; this result provides strong support for turning off lights at night to reduce bird-building collisions. Although we found no relationship between PLP and collisions, additional research is needed to better understand bird responses to polarized light. Fully understanding how different aspects of light influence bird-building collisions can inform conservation efforts to reduce this major threat to birds.

1. Introduction

Building collisions are a major source of avian mortality, killing 365–988 million birds each year in the United States (Loss et al., 2014). Bird-building collisions occur primarily at glass surfaces, as birds often fail to perceive panes that are transparent or that reflect sky and/or vegetation (Klem, 1989). Susceptibility to collisions could be exacerbated at night, when nocturnally migrating birds can be attracted to or disoriented by lighting emanating from windows (Evans Ogden, 2002; Keyes and Sexton, 2014; Parkins et al., 2015). Supporting these observations, studies have shown that the area and/or proportion of buildings covered by glass and the distance of vegetation from buildings are positively correlated with collisions (e.g., Cusa et al., 2015; Gómez-Martínez et al., 2019; Hager et al., 2013; Klem et al., 2009), and further, that most collision victims are nocturnal migrants (Arnold and Zink, 2011; Loss et al., 2014; Nichols et al., 2018). However, few studies have formally analyzed the relationship between artificial light at night (ALAN) and building collisions despite the oft-cited importance of this factor. Moreover, nearly all bird-building collision studies assessing the role of lighting have drawn conclusions based only on light visible to humans.

ALAN changes natural patterns of light and dark in ecosystems, influencing animal behaviors and activity patterns (Longcore and Rich, 2004). At broad scales, ALAN can disorient birds and cause them to concentrate in urban areas (La Sorte et al., 2017; McLaren et al., 2018; Van Doren et al., 2017). At finer scales, light emitted from and near

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buildings and other structures can attract birds, particularly on nights with low clouds and/or visibility (Avery et al., 1976; Kerlinger et al., 2010; Rebke et al., 2019). Anecdotal evidence suggests that ALAN contributes to bird-building collisions, but few peer-reviewed studies have formally analyzed this relationship. One study that found an association between light emission and bird collisions was unable to isolate the correlated effects of light emission and glass area (Parkins et al., 2015). Another study showed that more birds were killed at a convention center when more window bays were lighted (Winger et al., 2019), but this study focused on one exceptionally large, glassy building. Thus, further research is needed to formally assess effects of ALAN relative to other variables influencing bird-building collisions and at a broader range of building types.

In addition to ALAN, other aspects of light may play a role in bird-building collisions, as birds have different visual systems and perceive light differently than humans (Maier and Bowmaker, 1993; Martin, 2011). A poorly understood aspect of avian vision is the degree to which birds detect polarized light and whether it influences behavior and collision risk. Sunlight is *unpolarized* before entering earth's atmosphere, meaning the electric field vectors (*E*-vector) of light waves vibrate equally in all directions (Fig. 1A). Light is *polarized* when the light source (i.e., *incident light*) reflects off a surface that causes the E-vector of reflected light to vibrate in a single plane. The *degree of polarization* is the percentage of reflected light that is polarized, which depends on characteristics of the reflecting surface and the angle of incident light. Generally, smooth, dark surfaces and low angles of reflection cause high degrees of polarization (Umov, 1905).

In nature, the most common terrestrial source of polarized light is water. However, any smooth, dark surface can polarize light, and human-built surfaces such as buildings, solar panels, and roads create *polarized light pollution* (PLP), which is analogous to ALAN in changing naturally occurring patterns of polarized light in ecosystems (Horváth et al., 2009, 2014). PLP is characterized by high degrees of polarization reflected at a horizontal angle, and several animal species perceive horizontally polarized light to locate water-associated breeding areas and food sources (Horváth et al., 2009). These species can be attracted to and entrapped by PLP. For example, aquatic insects like caddisflies (Trichoptera) land in large numbers and attempt to oviposit on highly polarizing artificial surfaces like windows (Kriska et al., 2008; Robertson et al., 2010). Birds may also detect polarized light and use it as a navigational cue; specifically, migrating songbirds may use polarization patterns in the sky at twilight to calibrate their magnetic compass (Able and Able, 1995; Muheim et al., 2006, 2007, 2009). Very little research has assessed if birds are also attracted to polarized light reflected from natural or artificial surfaces, but anecdotally, water birds have been found dead or stranded at night on asphalt surfaces that produce PLP by reflecting light from streetlamps (Horváth et al., 2009). Experiments also suggest that some songbirds are attracted to horizontal surfaces that polarize light (Easthausen, 2015). Despite the potential for birds to perceive polarized light, no research has addressed whether PLP at buildings helps explain variation in bird collision rates.

We conducted bird collision monitoring at 48 façades of 13 buildings in Minneapolis, Minnesota, USA, to assess if collisions are related to: (1) ALAN emission from windows, independent of glass area, and (2) the degree of polarized light reflected from building surfaces. We hypothesized that collisions would positively correlate with both ALAN and PLP due to their potential attraction and entrapment effects. As migratory bird populations have declined precipitously over the last several decades (Rosenberg et al., 2019), studying potential factors contributing to mortality, including effects of ALAN and PLP on bird-building collisions, will improve understanding and mitigation of factors contributing to avian declines.

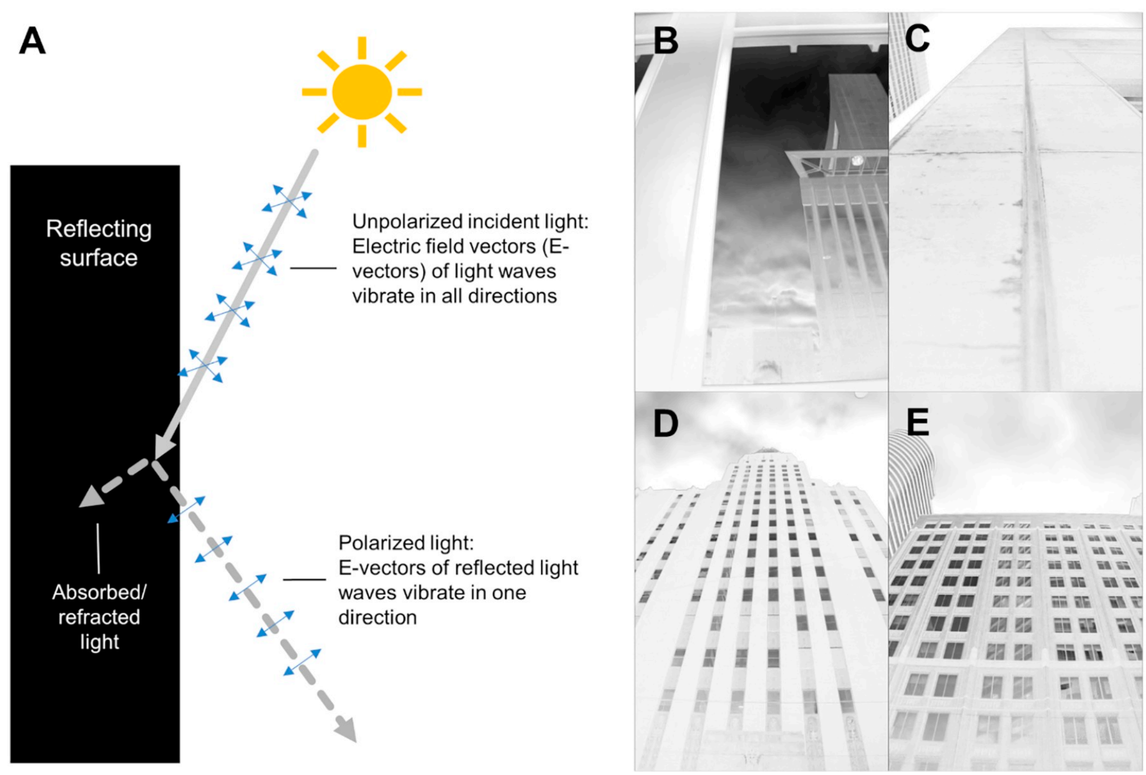

Fig. 1. Illustrations of polarized light. A) Example of how unpolarized incident light (e.g., sunlight) becomes polarized after reflecting off a surface; B–E) Examples of images depicting degree of polarized light reflected from building façade surfaces. Darker areas indicate surfaces with high degrees of polarization (i.e., black pixels represent 100% polarization) and lighter areas indicate surfaces with low degrees of polarization (i.e., white pixels represent 0% polarization). B) Glass surface; C) Travertine surface; D, E) Different parts of the same building façade.

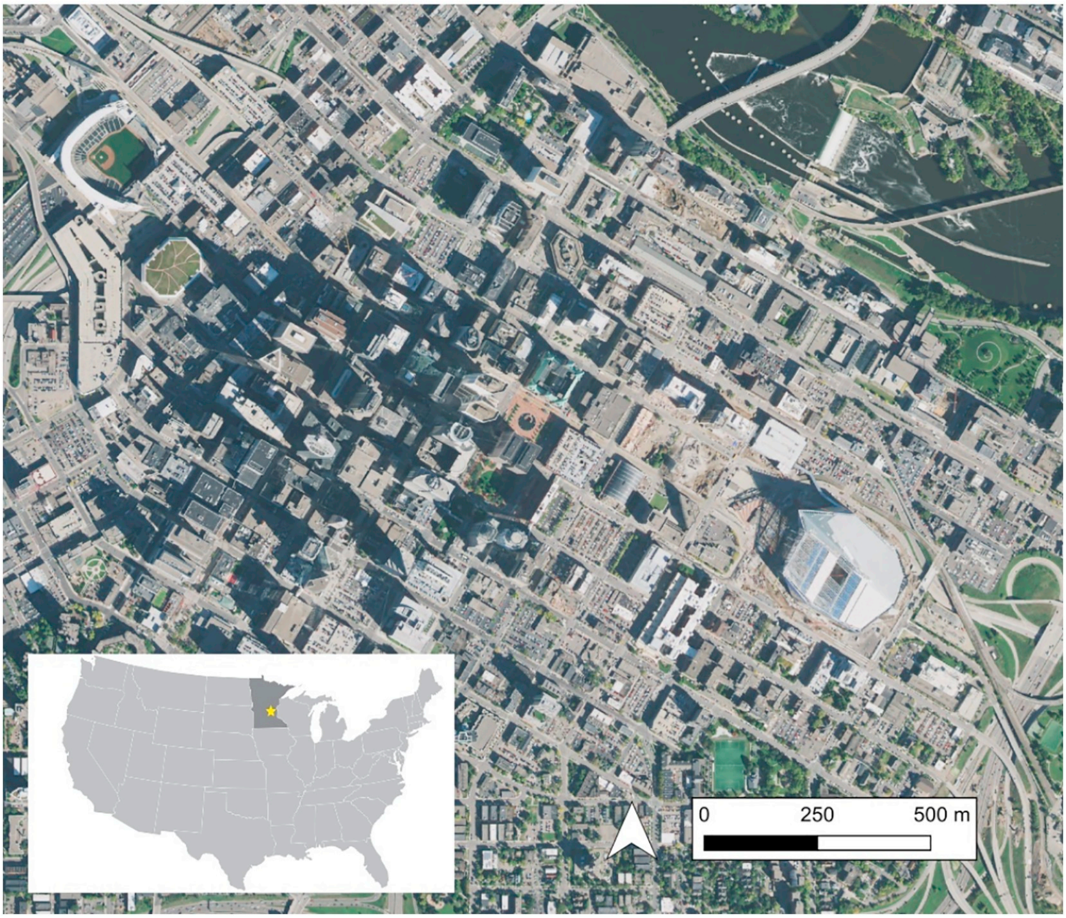

Fig. 2. Image of study area containing buildings monitored for bird collisions in downtown Minneapolis, Minnesota, USA, 2017–2018. Individual buildings are not identified due to terms of the funding contract. (image source: USDA NAIP plus aerial imagery).

2. Material and methods

2.1. Study site and building selection

We conducted this study in downtown Minneapolis, Minnesota, USA (Fig. 2) as part of a larger study investigating factors influencing variation in collisions among buildings and through time (Loss et al., 2019). As a highly urbanized city located adjacent to the Mississippi River and within the Mississippi Flyway, Minneapolis was identified as one of the top ten most dangerous cities for migratory birds in spring and fall based on the amount of light pollution emitted and the number of birds moving through the area (Horton et al., 2019).

As part of the larger study, we selected 21 buildings using criteria to capture spatial variation and a range of expected collision numbers; 16 were selected from a set of 64 buildings—which were monitored by Audubon Minnesota's Project BirdSafe program from 2007 to 2016—to include a broad range of previously observed collision numbers, maximize access to as many façades as possible, and capture varying distances from the Mississippi River. Four previously unmonitored buildings were selected randomly with the same criteria, and one additional building (a multi-use stadium) was included due to funder interests.

For this study of ALAN and PLP effects, we collected data from individual building façades, which we defined as discrete faces of buildings oriented in different directions. We only analyzed a subset of 13 buildings for this study because security and access limitations prevented us from taking high-quality photos of some buildings. For some irregularly shaped buildings, we combined data from adjacent façades when we were unable to determine the façade at which collisions occurred. We also excluded four façades from analysis because we were unable to obtain reliable estimates of glass, ALAN, and/or PLP variables due to unusual façade characteristics (e.g., angled glass with setbacks). We ultimately collected data from 48 façades that are part of the 13 buildings. Nonetheless, this study captured a variety of building types, including low-rises, high-rises, and the stadium, as well as a broad range of observed collision numbers and building characteristics (e.g., building surfaces).

2.2. Collision monitoring

In 2017 and 2018, we surveyed buildings every morning at approximately sunrise during spring migration (15 March to 31 May), early summer (1 Jun to 30 Jun), and fall migration (15 August to 31 October). On a subset of dates, we conducted additional mid-day and late afternoon surveys at all buildings to evaluate the number of bird collisions throughout the day. For each survey, a trained surveyor walked a fixed route and monitored accessible portions of all 48 façades. To account for time-of-day and lighting effects, surveyors began routes at different buildings each day and monitored buildings clockwise on even dates and counter-clockwise on odd dates. During spring 2017, buildings were assigned to two separate routes, and the start building for each route shifted to the next building in the sequence each day. Because surveyors were able to complete both routes within ~1.5–2.5 h, we merged the routes starting June 2017 and used a random number generator to select the start building each day.

For all birds found within ~5 m of a building façade, surveyors entered the date, time, location, species, and photos in an ESRI ArcGIS Online form. Most dead birds were placed in sealable plastic bags and stored in freezers. For birds found alive but stunned after colliding with a building, surveyors attempted to capture the bird and place it in an unlined paper bag. Captured birds were later released in parks outside of downtown Minneapolis or brought to a rehabilitation center. Birds were collected under U.S. Fish & Wildlife Service Scientific Collecting Permit #MB05120C-1 and Minnesota Department of Natural Resources Salvage Permit #20412. Animal handling protocols were approved by the Institutional Animal Care and Use Committee (#AG-17-6).

For this study, we considered unadjusted (i.e., raw) collision counts, including both fatal and non-fatal collisions. Our larger study included experimental trials to quantify rates of bird carcass removal by humans and scavengers and rates of surveyor detection of carcasses (Bracey et al., 2016; Riding and Loss, 2018); however, we did not have enough replicates of these trials at individual façades to produce façade-level estimates accounting for these factors. We also removed from counts any birds that were potential skyway collisions (i.e., birds that may have collided with glass walkways connecting the monitored building façades) or parts of birds that may have resulted from predation instead of collisions. Although these records likely include some collisions with study buildings, we removed them to produce conservative raw collision counts. We were also unable to account for birds that survived collisions and flew away before surveyors could detect them. The raw counts are therefore underestimates of the actual number of birds that collided.

2.3. Measuring artificial light at night

Of note for the following variables, we treated windows and glass as different features; windows were considered areas of glass with openings behind them (i.e., glass that allows light to penetrate into or emanate out of buildings) while glass included windows and all types of reflective glass surfaces without openings behind them (e.g., mirrored glass covering concrete walls). For each of the 48 building façades, we measured the surface area of windows lighted at night (hereafter: lighting area) and the proportion of all glass lighted at night (hereafter: lighting proportion). For lighting proportion, we divided lighting area by area of all glass surfaces because we expected all types of glass to influence collisions. To generate these variables, we first calculated glass area by taking direct measurements of glass panes using measuring tape whenever possible. When direct measurements were not possible, we photographed building façades and used ImageJ (Schneider et al., 2012) and a known-dimension reference (e.g., one directly-measured edge of a glass pane) to calculate the area of every pane of glass. To measure ALAN and to capture night-to-night lighting variation, we photographed all building façades on three separate nights at least 1 h after sunset but before midnight during collision-monitoring seasons. Using these photos, we counted the number of windows emitting any amount of light and calculated lighting area by summing the area of all lighted windows for each night and then averaging across all nights. Finally, we calculated lighting proportion by dividing average lighting area by glass area. Our approach of obtaining lighting data on three nights for each building did not capture all lighting variation throughout the study period. However, the average standard deviation of lighting across the three nights for all façades was 5% (s for individual façades varied from 0 to 29.7%), which indicates that we still captured substantial lighting variation using our approach that was limited by logistical constraints.

We also calculated several glass variables for each façade to account for correlations between lighting and glass and to compare their relative importance in predicting bird collisions. These glass variables included glass area (sum of area of all glass panes), glass proportion (glass area divided by the area of each façade), maximum pane area (area of largest individual glass pane), and average pane area (average area of all glass panes).

2.4. Measuring polarized light pollution

To measure PLP for each building façade, we used a manual polarimeter (Estrato Research and Development, 2019), which consisted of a Canon EOS 650D DSLR camera and a Tamron 18–200 mm lens customized with a rotating polarized light filter. For each surface type on a façade (e.g., glass, brick, concrete), we captured a set of three images with the filter rotated to a different position for each image according to manufacturer instructions. To capture the highest degree of polarization for each surface, we tilted the camera lens upward to ~56 degrees from horizontal, which is the angle at which light reflected from glass is maximally polarized (Brewster, 1815). All photos were taken during the day between 0545 and 1400 h in cloudy or overcast conditions to capture incident light scattered from multiple directions. Photos were then processed in Polarworks (Estrato Research and Development, 2019), a program that combines the three images and generates a modified image displaying polarization characteristics for each surface in the photo (Fig. 1B–E).

Using ImageJ and the modified images from Polarworks, we quantified PLP metrics for each façade. We converted images to 8-bit format and used the Polygon Selections tool to draw a polygon on each façade surface of interest. We then used the Measure tool to generate mean pixel intensity in the range of 0 to 255, where 0 indicates pure black and 255 indicates pure white. We repeated this process at least three times for each surface of interest to ensure consistent measurements. By dividing the mean pixel intensity by 255 and multiplying by 100, we obtained the percentage of "whiteness" of each selected area. We subtracted this result from 100 to calculate the degree of polarization of each surface, represented by the percentage of "blackness" of the pixels in the selected area. We then calculated the overall degree of polarization for each building façade by estimating the percentage of each façade surface using ImageJ and multiplying the percentage of each surface by its degree of polarization to generate a weighted average (hereafter: polarization index) that ascribes greater weight to surfaces comprising a larger portion of the façade. In addition to polarization index, we measured three other polarized light variables for each façade: degree of polarization reflected from the most-polarizing surface (hereafter: maximum polarization), degree of polarization reflected from the least-polarizing surface (hereafter: minimum polarization), and the difference between the maximum and minimum degrees of polarization (hereafter: polarization contrast). All PLP, ALAN, and glass variables are summarized in Table 1.

2.5. Statistical analysis

All analyses were conducted in R 3.6.1 (R Core Team, 2019). To determine which variables to formally analyze, we first tested for highly

Table 1
Definitions for all artificial lighting, glass, and polarized light variables measured for each building façade.

Variable	Definition
Lighting area	Surface area of windows lighted at night
Lighting proportion	Proportion of all glass lighted at night
Glass area	Surface area of all glass panes
Glass proportion	Glass area divided by façade surface area
Average pane area	Average surface area of all glass panes
Maximum pane area	Surface area of largest individual glass pane
Polarization index	Weighted average of the degree of polarization reflected from the façade
Maximum polarization	Degree of polarization reflected from the most-polarizing surface
Minimum polarization	Degree of polarization reflected from the least-polarizing surface
Polarization contrast	Difference between maximum and minimum polarization

correlated pairs of variables among glass variables (glass area and proportion, and maximum and average pane area), ALAN variables (lighting area and proportion), and PLP variables (polarization index, maximum and minimum polarization, and polarization contrast). Only polarization contrast and minimum polarization were highly correlated ($r > |0.7|$). Because Akaike's Information Criterion adjusted for small sample sizes (AIC_c; Burnham and Anderson, 2002) showed minimum polarization to be a better predictor of collisions than polarization contrast (see Table 3), we excluded polarization contrast from further analyses.

We used R package *lme4* (Bates et al., 2015) to construct generalized linear mixed models (GLMM) with unadjusted collision counts as the response variable, the above ALAN and PLP variables as fixed effects, and building as a random effect to account for non-independence of individual façades nested within the same building. We also included an offset term for the number of collision surveys conducted at each façade to account for varying effort that arose due to occasional access restrictions (e.g., construction and public events). Because the collision count data were overdispersed, we used negative binomial GLMMs. To evaluate the importance of each ALAN and PLP variable, we constructed a model including additive effects of all five ALAN and PLP variables and conducted a likelihood ratio test using function 'drop1'. We validated the result by constructing models with all additive combinations of lighting and polarized light variables and comparing model fit using AIC_c. Finally, to evaluate the importance of ALAN and PLP variables relative to glass variables, we used AIC_c to compare fit of all single-variable models.

3. Results

We observed 768 fatal and non-fatal bird collisions at the 48 surveyed façades (range: 0–194 per façade). Based on likelihood ratio tests, we found that lighting area and lighting proportion had statistically significant positive associations with numbers of collisions, with lighting area as the most informative predictor (lighting area: $\chi^2 = 22.83$, $p < 0.0001$, df = 1; lighting proportion: $\chi^2 = 6.57$, $p = 0.01$, df = 1), and that polarized light variables were unassociated with collisions (Appendix A, Table A1). This result was supported by AIC_c rankings of all possible additive models containing ALAN and PLP variables (Table 2); specifically, the top model included positive effects of lighting proportion and lighting area, no PLP variables, and had an AIC_c weight ~four times greater ($w_i = 0.79$) than the next best model ($w_i = 0.21$).

AIC_c comparisons of all single-variable models for ALAN, PLP, and glass variables showed that lighting area was the best predictor of collisions, followed by average pane area (Table 3); both of these variables were positively associated with collisions. No other single-variable ALAN and glass area models were competitive, having $\Delta AIC_c \geq 7$ but performing better than the null model. All single-variable polarized light models had $\Delta AIC_c > 22$ and ranked behind the null model. To confirm the significance of lighting and glass independent of each other, we constructed a model with the top two variables, lighting area and average pane area; both variables had significant ($p < 0.0001$) positive associations with collisions (incidence rate ratios: lighting area: 1.57 (95% CI: 1.25–1.97); average pane area: 2.06 (95% CI: 1.53–2.77)).

Table 2
Model selection results for analysis of bird-building collisions in relation to artificial night lighting (lighting proportion, lighting area) and polarized light variables (polarization index, maximum polarization, minimum polarization). All models were negative binomial GLMMs with building as a random effect and number of surveys as an offset term. Only models that do not include uninformative parameters and performed better than the null model are shown.

Model	AIC_c	ΔAIC_c	df	Weight
Lighting proportion + Lighting area	292.2	0	5	0.79
Lighting area	294.9	2.7	4	0.21
Lighting proportion	310.7	18.5	4	< 0.001
Null	317.6	25.4	3	< 0.001

β for top model: Lighting proportion: 0.01 (95% CI: 0.004–0.02); Lighting area: 0.02 (95% CI: 0.01–0.03).

Table 3
AIC_c table comparing fit for all single-variable models for analysis of bird-building collisions in relation to individual artificial night lighting, polarized light, and glass variables. All models were negative binomial GLMMs with building as a random effect and number of surveys as an offset term. Incidence rate ratios and 95% confidence intervals also provided for each variable to show effect size.

Model	AIC_c	ΔAIC_c	df	Weight	IRR	95% CI
Lighting area	294.9	0	4	0.744	3.41	2.56–4.55
Average pane area	297.2	2.3	4	0.237	2.75	1.98–3.82
Maximum pane area	302.3	7.4	4	0.018	3.5	1.98–6.17
Glass area	310.3	15.4	4	< 0.001	2.07	1.25–3.43
Lighting proportion	310.7	15.8	4	< 0.001	16.3	3.17–83.5
Glass percentage	316.7	21.8	4	< 0.001	5.25	0.92–30.1
Null	317.6	22.7	3	< 0.001	0.01	0.01–0.03
Minimum polarization	318.2	23.3	4	< 0.001	18.1	0.29–1129
Maximum polarization	319.7	24.8	4	< 0.001	2.34	0.13–42.7
Polarization index	319.8	24.9	4	< 0.001	2.07	0.09–44
Polarization contrast	319.9	25.0	4	< 0.001	0.69	0.06–7.5

4. Discussion

This study was the first to simultaneously evaluate how bird-building collisions are influenced by two different types of light pollution: artificial light at night (ALAN) emanating from building windows and polarized light pollution (PLP) reflected from building surfaces. Our results provide evidence that ALAN emanating from building windows correlates with bird-building collisions independent of glass area. Specifically, we found that the area of lighted windows and proportion of glass lighted at night were important predictors of collisions, and that lighting area in particular was a better predictor than glass area, glass percentage, and the maximum and average sizes of glass panes. However, we did not find evidence for an effect of polarized light pollution on collisions.

Most previous studies that found a relationship between collisions and ALAN at the level of entire buildings analyzed a light index calculated by multiplying percent lighting by the number of floors in each building to account for building size (Evans Ogden, 2002; Keyes and Sexton, 2014; Parkins et al., 2015). However, these studies did not or were unable to parse apart the effects of lighting and glass because the light index was strongly correlated with percent glass. We found that, at the level of individual building façades, lighting variables were not highly correlated with any glass variables, suggesting that these factors may vary independently when analyzed at the façade level instead of the building level. Indeed, a companion study assessing building-level collision correlates analyzed lighting area at the building scale for all 21 study buildings and found a stronger correlation between lighting area and glass area (Loss et al., 2019). These differences between façade- and building-level results suggest that analyses focusing on individual façades may reveal additional predictors of collisions that have not been identified at larger scales. Our finding that lighting area was a significant predictor of collisions independent of glass area also suggests that lighting could partially contribute to the frequently identified importance of glass area in past studies (e.g., Hager et al., 2013; Schneider et al., 2018). However, we expect the reflective and/or transparent properties of glass to also influence collisions independent of lighting, especially for bird collisions that occur during daytime when ALAN effects are minimal (e.g., Ocampo-Peñuela et al., 2016).

We also found that, in addition to lighting area, lighting proportion was an important predictor of collisions. Depending on façade size and glass area, lighting proportion represents different amounts of light emitted from each façade, and therefore, the mechanism for the effect of lighting proportion on collisions is uncertain. We hypothesize that higher proportions of lighting may represent lighted windows occurring closer together, which could create more contiguous areas of lighting that likely play a greater role in attracting birds than isolated windows emitting light (see also Loss et al., 2019). Hence, our results may indicate that buildings with large areas of lighted windows and high proportions and/or contiguous areas of lighted glass are especially dangerous for birds, attracting and killing migrating birds to a greater degree than buildings with smaller, less contiguous areas of lighted glass. Further research investigating these and other metrics of ALAN emission from building windows, including metrics that explicitly capture lighting and glass contiguity (e.g., average distances among windows or fragmentation indices used in spatial ecology), may help clarify mechanisms for the role of lighting in bird-building collisions.

Our finding that ALAN was an important predictor of bird-building collisions at individual building façades has implications for management efforts designed to reduce this threat to bird populations. By quantifying the relative effect of ALAN compared to other potential collision correlates, we provide a stronger, data-supported argument for lighting reduction efforts (e.g., "Lights Out" programs; National Audubon Society, 2019) that recommend turning off lights and/or shading windows at night during spring and fall migration to reduce collisions. Along with past research, these results provide evidence that significant reductions in bird-building collisions may be achieved by implementing a combination of measures that reduce ALAN emitted from windows, break up reflections from and reduce transparency of glass, and focus mitigation steps on glass near existing vegetation (Gelb and Delacretaz, 2009; Klem et al., 2009; Schneider et al., 2018). Notably, we were only able to obtain lighting data before midnight due to logistical constraints. Because most "Lights Out" programs are in effect after midnight, future studies should assess how lighting conditions after midnight and throughout the night influence collisions. Additionally, we only quantified the area of glass that appeared to be lit from within each building and lacked the equipment to analyze other properties of artificial night lighting (e.g., color, intensity) or other light sources, such as those on exterior building surfaces or ground-based lighting features. Because shutting off high-intensity exterior lights virtually eliminates disruptive effects on nocturnally migrating birds (Van Doren et al., 2017), and lights with varying spectral properties (e.g., colors) have differential effects on various wildlife taxa (Longcore et al., 2018), future collision studies should also evaluate the importance of exterior building lighting and the direction, intensity, and spectral characteristics of lighting relative to area of lighted windows. Such studies will be especially important as building managers and municipalities increasingly adopt high-efficiency light-emitting diodes (LEDs), which typically produce light with short wavelengths that increase sky glow (i.e., reduced night-sky visibility caused by atmospheric scattering of light; Luginbuhl et al., 2014; Kinzey et al., 2017), obscuring navigation cues (Poot et al., 2008) and attracting birds to urban areas (LaSorte et al., 2017; McLaren et al., 2018). Furthermore, decreasing costs of energy consumption associated with LEDs allow for increased installation of lighting in areas that were previously unlit (Kyba et al., 2017), potentially exacerbating the effects of ALAN on migrating birds.

We found no associations between bird-building collisions and the variables we measured to quantify polarized light reflected from buildings. This result suggests that collisions may not be driven by avian responses to PLP. However, the strong effect of ALAN in our analysis may overwhelm any effect of polarized light. Specifically, because PLP can occur both during the day and at night—and because artificial light sources diminish polarized light signals (Kyba et al., 2011)—ALAN emanating from the interior of windows likely reduces polarized light reflected from the exterior of these windows. Because ALAN reduces the effect of PLP, additional research to assess both types of light in a more controlled manner may help parse apart their effects and confirm our result of PLP being unassociated with bird collisions. One approach to separately evaluate PLP's effects could be to assess it only in relation to bird collisions that occur during daytime and near twilight, when ALAN effects are reduced. Another approach could entail focusing on collisions of bird species that are likely to respond to polarized light, such as songbirds for which evidence exists of the potential use of polarized light as a navigational cue (e.g., White-throated Sparrow [*Zonotrichia albicollis*; Muheim et al., 2009] and Savannah Sparrow [*Passerculus sandwichensis*; Able and Able, 1995, Muheim et al., 2006, 2007]). However, as few studies have experimentally determined which species respond to polarized light, additional research is necessary to understand avian responses to PLP and to design rigorous studies of the relationship between polarized light and bird collisions.

Although we found no evidence that PLP affects collisions, reducing PLP may change properties of glass in ways that reduce, or possibly increase, collisions. One study showed that adding white, non-polarizing grid patterns to solar panels reduced the attractiveness of the panels to insects that are entrapped by PLP (Horváth et al., 2010). Hence, adding contrasting, non-polarizing patterns to glass surfaces and using smaller panes could reduce the degree of polarization reflected from buildings while also breaking up reflections of visible light that make glass dangerous for birds, especially given that this and previous studies show that sizes of individual panes influence collisions (Kahle et al., 2016). A similar effect might come from constructing buildings with higher proportions of low-polarizing surfaces, such as brick, which would reduce the amount and proportion of glass with which birds can collide. However, detecting polarized light may help some bird species perceive glass as they approach buildings and therefore reduce fatal collisions (Robertson, B.A., unpublished results), in which case, reducing the polarized light signature of glass could increase collisions. Furthermore, turning off lights within buildings would have the additional effect of increasing PLP reflected from windows and could help birds better detect buildings. To better inform collision reduction strategies, further research is needed to understand whether polarized light represents a source of pollution that attracts and entraps birds near buildings or a potential tool to help reduce collisions.

5. Conclusions

Using data from 48 façades at 13 different buildings, we show that two variables capturing artificial lighting at night (ALAN)—area of windows lighted and proportion of glass lighted—were important predictors of bird-building collisions. This study demonstrates an association between bird-building collisions and ALAN independent of the effect of glass area, and indicates that lighted window area can be a better predictor of collisions than glass area. This finding provides strong support for recommendations to turn off lights or shade windows at night to help reduce bird collisions during spring and fall migration. Existing lighting reduction efforts (e.g., Audubon's "Lights Out" program) implemented in cities throughout North America are therefore likely effective for reducing collision mortality, and expansion and refinement of such programs in urban areas of all sizes should further reduce this threat to bird populations. Although we found no support for a relationship between polarized light pollution (PLP) and collisions, additional research is needed to better understand avian perception and responses to polarized light and to parse apart the effects of ALAN and PLP on bird-building collisions. Fully understanding how different aspects of light influence bird-building collisions can inform conservation efforts to reduce this major threat to birds.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Results of likelihood ratio test (LRT) with single-term deletions of polarized light and artificial night lighting variables. Differences in AIC values between the full model ("None") and other models represent the change in AIC associated with dropping the variable from the full model; thus, higher AIC values represent greater reduction in model support with exclusion of the focal variable. Beta coefficients and 95% confidence intervals to illustrate direction of effect are from the full additive negative binomial GLMM with building as a random effect and number of surveys as an offset term.

Variable dropped	AIC	LRT	p (chi)	β	95% CI
None	295.06				
Polarization index	293.09	0.0331	0.85571	−0.001	−0.012–0.010
Maximum polarization	293.15	0.0879	0.76683	−0.001	−0.009–0.007
Minimum polarization	294.46	1.3980	0.23706	0.008	−0.002–0.018
Lighting proportion	299.63	6.5709	0.01037	0.012	0.004–0.021
Lighting area	315.89	22.8270	1.773e-06	0.022	0.015–0.030

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