

Changing vertical substrate color and pattern to reduce seabird collisions associated with artificial light

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ABSTRACT

The magnitude and extent of increased artificial light at night is a growing concern for various species and ecosystems, including procellariiform seabirds. Artificial light on coastlines, ships, and fossil fuel platforms attracts procellariiforms that are foraging or migrating at night, causing fallout at illuminated sites that lead to fatalities through exhaustion, dehydration, predation, vehicle collisions, and impact injuries. To assess effects of different illuminated vertical substrates on collisions, we suspended different colored (white, black, and beige) and patterned (plain, grid, and striped) cloth sheets in a colony of *Hydrobates leucorhous* (Leach's Storm-Petrel) on 40 nights in 2024 and 2025. Sheets were illuminated with a white floodlight using 5-min on/off intervals, and sheet treatment was changed every 30 min. Petrels were 9 times more likely to collide with colored sheets when lights were on rather than off, nearly 3 times more likely to collide with white than black sheets, and between 2 and 3 times more likely to collide with plain than patterned sheets. Despite decreased collisions with darker sheets, petrels flying overhead were noticeably repelled by light, offering support for the hypothesis that artificial light causes disorientation rather than attraction at small spatial scales. Dark colors or patterned walls could reduce fallout and collisions for seabirds as well as for migrating passerines and could have implications for conservation of other organisms affected by artificial light.

Keywords: artificial light, building collisions, light attraction, procellariiform, seabird, storm-petrel

How to Cite

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LAY SUMMARY

- Many seabirds are attracted to and disoriented by human light sources at night, causing birds to strand on land or on offshore structures and vessels.
- Stranded individuals are vulnerable to exhaustion, dehydration, starvation, predation, and collisions with buildings or vehicles, all of which contribute to mortality.
- At many stranding locations, lights cannot be turned off due to concerns about worker safety.
- Using sheets to ensure birds were unharmed, we tested if changing colors (white, black, and beige) or patterns (plain, gridded, and striped) of walls could reduce collisions at a colony of *Hydrobates leucorhous* (Leach's Storm-Petrel).
- Storm-petrels were 9 times more likely to collide with lit sheets than unlit sheets, but were repelled by light when flying, suggesting that lights cause disorientation.
- Storm-petrels were less likely to collide with darker and patterned surfaces, which could be successful at reducing associated fatalities at stranding locations where lights must remain on.

Cambios en el color y el patrón de los sustratos verticales Para reducir las colisiones de aves marinas asociadas con la luz artificial

RESUMEN

La magnitud y extensión del aumento de la luz artificial nocturna constituye una preocupación creciente para diversas especies y ecosistemas, incluidas las aves marinas procelariiformes. La luz artificial en costas, embarcaciones y plataformas de combustibles fósiles atrae a los procelariiformes que se encuentran forrajeando o migrando durante la noche, provocando efectos adversos en los sitios iluminados que derivan en mortalidad por agotamiento, deshidratación, depredación, colisiones con vehículos y lesiones por impacto. Para evaluar los efectos de distintos sustratos verticales iluminados sobre las colisiones, colgamos telas de diferentes colores (blanco, negro y beige) y patrones (lisas, cuadrículadas y rayadas) en una colonia de *Hydrobates leucorhous* durante 40 noches de 2024 y 2025. Las telas fueron iluminadas con un reflector de luz blanca utilizando intervalos de 5 min de encendido/apagado, y el tratamiento de las telas se modificó cada 30 min. Los petreles tuvieron una probabilidad 9 veces mayor de colisionar con las telas cuando las luces estaban encendidas que cuando estaban apagadas, casi 3 veces mayor de colisionar con telas blancas que con negras, y entre 2 y 3 veces mayor de colisionar con telas lisas que con telas con patrones. A pesar de la reducción de las colisiones

con telas más oscuras, los petreles que volaban por encima mostraron una clara evitación de la luz, lo que aporta evidencia a favor de la hipótesis de que la luz artificial provoca desorientación más que atracción a escalas espaciales pequeñas. Los colores oscuros o las superficies con patrones podrían reducir los efectos adversos y las colisiones tanto de aves marinas como de aves canoras migratorias, y podrían tener implicancias para la conservación de otros organismos afectados por la luz artificial.

Palabras clave: atracción por la luz, ave marina, colisiones con edificios, *Hydrobates leucorhous*, luz artificial, procelariiforme

INTRODUCTION

Approximately 23% of Earth's land-surface is polluted by artificial light at night (ALAN) (Falchi *et al.* 2016), and global coverage continues to grow by up to 9.6% each year (Kyba *et al.* 2023). ALAN affects behavior, community structure, and physiology in a diversity of organisms, including aquatic invertebrates (Ludvigsen *et al.* 2018), plants (Bennie *et al.* 2016), terrestrial insects (Owens and Lewis 2018), freshwater and marine fish (Riley *et al.* 2012), sea turtles (Tuxbury and Salmon 2005), bats (Voigt *et al.* 2018), and birds (Longcore *et al.* 2012, Van Doren *et al.* 2017, Rebke *et al.* 2019). Growing use of white light-emitting diodes (LEDs) has compounded concerns with increasing light pollution (Zissis and Bertoldi 2014), which although energy-efficient (Schubert and Kim 2005), are often broad-spectrum and rich in shorter wavelength light that interrupts a variety of biological processes (Gaston *et al.* 2012, Rivas *et al.* 2015).

Positive phototaxis (attraction to light sources) occurs in all preceding taxa, particularly insects, bats, and passerines. Seabirds within the Order Procellariiformes (e.g. shearwaters, petrels, storm-petrels, and albatrosses) are vulnerable to ALAN attraction and disorientation, characterized as directionless or otherwise altered movement in lit areas. The IUCN includes ALAN as a potential threat for 30% of threatened procellariiforms (IUCN 2025). ALAN along coastlines, on ships, and on fossil fuel platforms can attract seabirds and lead to strandings, also referred to as fallout (Rodríguez *et al.* 2017b). Fallout is often associated with collisions at illuminated facilities, causing fatalities through impact injuries or by increasing vulnerability to other threats, such as exhaustion, dehydration, starvation, predation, or vehicle collisions (Reed *et al.* 1985, Rodríguez *et al.* 2012, 2014, Ronconi *et al.* 2015, Guilford *et al.* 2019). Attraction to oil and gas platforms can also cause oiling or incineration from flares (Ronconi *et al.* 2015). Fledgling procellariiforms are more likely to strand than are adults (Gjerdrum *et al.* 2021, Burt *et al.* 2024) and fallout occurs in higher numbers on nights with low moonlight, onshore wind, and overcast skies (Telfer *et al.* 1987, Syposz *et al.* 2018, Wilhelm *et al.* 2021).

Estimating how many individuals are affected by ALAN attraction is difficult, but some populations appear to be uniquely vulnerable. For example, ~14% of *Calonectris borealis* (Cory's Shearwater) fledglings on Tenerife Island are attracted to ALAN sources each year (Rodríguez *et al.* 2015). In Atlantic Canada, nearly 8,000 total seabirds were reported stranded between 1998 and 2018, most of which were on fossil fuel platforms and support vessels (Gjerdrum *et al.* 2021). In one Newfoundland study, however, over 1,000 stranded *Hydrobates leucorhous* (Leach's Storm-Petrel) were reported in a single night at a fish-processing plant, suggesting that 8,000 is a significant underestimate (Burt 2022). The proportion of fallout that leads to fatalities and whether ALAN contributes to population declines is unknown, but mortality could be between 6% and 43% of stranded procellariiforms for some populations (Podolsky *et al.* 1998). Carcasses can disappear

quickly due to scavenging, leading to an underestimation of at least 17% (Podolsky *et al.* 1998). Moreover, a study using model shearwaters had a searcher efficacy rate of 30–50%, with most detections in exposed locations (Sahin and Olson 2025). Mortality rate underestimates may be even higher for smaller species, such as storm-petrels, because they are less likely to be collected opportunistically by the general public and may be more likely to be depredated or scavenged (Rodríguez *et al.* 2014, 2017b).

Causes of procellariiform light attraction and disorientation are unclear, but a first hypothesis is that birds confuse light with bioluminescent prey that are common in some species' diets (Imber *et al.* 1975, Telfer *et al.* 1987, Collins and Bracken-Grisson 2024). A second hypothesis is that ALAN outshines celestial cues used for navigation or interferes with the light-dependent radical-pair process of magnetic field navigation, as occurs in passerines (Reed *et al.* 1985, Telfer *et al.* 1987, Wiltshko and Wiltshko 2019). Finally, nestlings of burrow-nesting procellariiforms, which as a group are more likely to be affected by ALAN than non-burrow-nesting procellariiforms, are accustomed to receiving food through burrow entrances and may associate light sources with food or be positively phototactic during the fledgling period to encourage exiting from burrows (D. Ainley personal communication cited by Rodríguez *et al.* 2017a), either to exercise wings or to leave the colony. Fledglings of burrow-nesting procellariiforms may also be more vulnerable to fallout due to their delayed eye development (Atchoi *et al.* 2020).

Turning lights off is the most successful method of mitigating light attraction (e.g. Rodríguez *et al.* 2014, Burt 2022) but is often not feasible when lights are required for human safety, such as at many types of commercial facilities. Other means of reducing attraction include shielding upward light (Reed *et al.* 1985) or reducing the quantity or intensity of lights (Burt *et al.* 2024). These methods can be implemented continuously or only during times when birds are particularly vulnerable to collisions, such as during peak fledge times (Miles *et al.* 2010, Burt 2022), low moonlight (e.g. Gjerdrum *et al.* 2021, Burt *et al.* 2024), strong onshore winds (Syposz *et al.* 2018, Wilhelm *et al.* 2021), or overcast conditions (Telfer *et al.* 1987, Wilhelm *et al.* 2021). Recent research has tested if changing light color can reduce the number of procellariiforms attracted to light, but results have differed among age classes, species, weather conditions, and types of study (Syposz *et al.* 2021, Atchoi *et al.* 2024, Brown *et al.* 2025, Middlemiss *et al.* 2025, Hutchinson 2026).

Changing colors of vertical surfaces has shown promise for preventing ALAN-associated collisions. In passerines, dark patterns on windows can prevent collisions (Rössler *et al.* 2015) and there is one account where changing the color of an illuminated wall from blue to yellow decreased the number of passerine collisions (Wang *et al.* 2011). Painting one blade of a wind turbine black reduced daytime avian casualties from turbine strikes by reducing motion smear (May *et al.* 2020).

However, although turning lights off inside a building reduced seabird collisions (Guilford *et al.* 2019), preventing seabird collisions associated with light attraction by changing colors, patterns, or other aspects of vertical substrates is, to our knowledge, untested.

Because procellariiform fallout is associated with collisions with surfaces, we hypothesized that altering colors or patterns of vertical surfaces would affect attraction and collisions of *H. leucorhous*. We predicted that because less light reflects off darker than lighter substrates, a darker vertical surface could decrease disorientation effects that contribute to collisions and fewer individuals would collide with darker versus lighter substrates. We also predicted that a patterned sheet could either provide navigational landmarks or decrease disorientation effects by interrupting reflected light, and therefore fewer individuals would collide with patterned versus solid-colored substrates. We also recorded temperature, wind speed, moon illumination, and cloud cover to determine if environmental factors that affect fallout were also associated with collisions in our experiments. To gauge how relevant increasing prevalence of LED lighting was to light attraction, we also evaluated coastal lighting visible from our study colony.

METHODS

Study Species and Location

Hydrobates leucorhous is listed as globally vulnerable by the IUCN, having declined by 54% in 44 years in Atlantic Canada, where 30% of the world's population breeds (BirdLife International 2018, COSEWIC 2020). Causes of declines are unknown but likely involve a variety of at-sea and onshore factors, including attraction to ALAN (Pollet *et al.* 2023).

Field work occurred on Bon Portage Island, Nova Scotia, Canada (43.4638°N, -65.7474°W), home to ~39,000 breeding pairs of *H. leucorhous* and the largest colony in Nova Scotia (Pollet and Shutler 2019). Access to the colony is affected by weather and research budgets. The experiment was conducted within the colony and the experimental location was selected for a high density of burrows and distance from an *Ardea herodias* (Great Blue Heron) heronry to prevent disturbing heron nestlings and from *Larus smithsonianus* (Herring Gull) nests to limit increased predation on petrels. The location was also ~300 m from a separate light attraction study facing the

opposite direction (Hutchinson 2026). Light from this separate study was only visible during foggy conditions at the surface color study site but could be seen from most of the *H. leucorhous* colony. Although there were concerns about individual birds breeding in the area being targeted by the lights and learning to avoid sheets over time, we were limited in site selection and decided to prioritize consistency.

Experimental Design

Different ~2.3 × ~2.6-m colored cloth sheets were suspended using 3-m tall mist net poles (Figure 1) in the *H. leucorhous* colony on 28 nights from July 1 through September 29, 2024. Dates were chosen to include both the non-fledging period, when only adults are present at the colony, and the fledgling period, which starts in early September and peaks around September 25 on Bon Portage (Pollet *et al.* 2021). In 2025, to broaden the purview of our study, we tested different patterned cloth sheets (Figure 1) on 12 nights from June 27 through August 16, 2025, but not during September due to a low number of collisions at that time in 2024. Sheets were illuminated with a commercially available warm white LED floodlight (3,000-K, 850 lumens, 13-W) with spectral peaks at 449.5 and 600.5 nm (Figure 2). The light was turned on and off in 5-min intervals, which was deemed short enough to be unaffected by changing *H. leucorhous* activity levels in the colony and changing weather effects throughout the night, but long enough for birds to react, and to be consistent with Hutchinson (2026). The light was positioned 3.5 m away from sheets, so that the entire sheet was illuminated evenly by the beam. If a bird collided with a sheet more than 4 times consecutively, the light was briefly turned off to allow those individuals to leave the area. If an individual did not leave the area on its own after 5 min, it was manually removed to a dark location.

In 2024, black, beige, and white microfiber sheets were selected to optimize reflectivity contrasts when testing different wall colors, but also to be representative of local wall colors, and were each lit with a single floodlight (Table 1). In 2025, vertical stripes and grid patterns were selected as being easy to replicate and to resemble corrugated metal or brick walls. Black fabric paint was used on white sheets to create patterns and covered ~50% of sheets (Figure 1). Vertical striped and gridded sheets were illuminated with 2 floodlights to match the amount



FIGURE 1. Illuminated plain white, striped, and gridded bedsheets suspended at the field site in the Bon Portage, Nova Scotia, Canada colony of *Hydrobates leucorhous*.

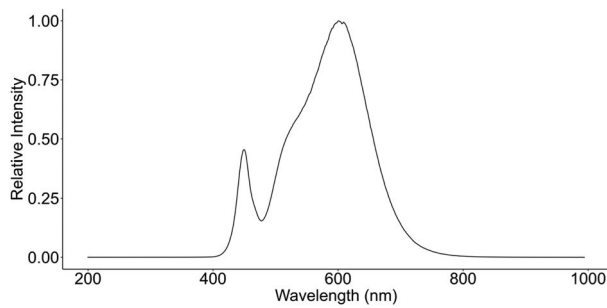


FIGURE 2. Emission spectrum from the LED floodlight used to illuminate sheets suspended in a *Hydrobates leucorhous* colony in Nova Scotia, Canada adjusted to relative intensity.

TABLE 1. Summary of sheet treatment types deployed in a *Hydrobates leucorhous* colony in Nova Scotia, Canada, and reflectance values.

Sheet color/pattern	Year	Number of floodlights	Reflectance (lux)
White	2024	1	17.8
Beige	2024	1	9.5
Black	2024	1	3.5
Plain white	2025	1	17.8
Gridded	2025	2	19.9
Vertical striped	2025	2	20.2

of light reflecting off the control sheet, which was a plain white sheet illuminated with only one floodlight (Table 1). Sheet colors were presented in a random order each night in 30-min intervals with 3 5-min light-off periods and 3 5-min light-on periods. Observations began ~2 hr after sunset (23:00 in July, 22:00 in September) and proceeded until 02:30 (3 cycles of each color) on all 2025 dates and from July 1 to July 15, 2024, and August 22 to September 29, 2024, or until 04:30 (4 cycles of each color) from July 24 to July 30, 2024.

Birds were counted during light-on periods in real time by 2 observers positioned within 1 m of each other and ~4 m from the fronts of the sheets. Sheet presentations during light-off periods were recorded with a FLIR C5 camera from July 1 to July 15 2024, but due to poor footage in fog, with an Ausdom AW615 1080P web camera (Aoni Electronics, Shenzhen, China) with an IR filter (RG 780IR, Edmund Optics, Barrington, NJ, USA) and 12-W, 880-nm Univivi Wide Angle IR Illuminator (12 LEDs) from July 24 to September 29, 2024, and on all 2025 dates. A computer program automated 5-min light intervals and saved videos to be reviewed later. Real-time observations had a wider field of view than did video recordings and allowed for better differentiation between multiple individuals colliding with a sheet and a single bird colliding with a sheet multiple times. A random subset of 15 light-on videos were compared to live counts to ensure consistency between counting methods and the counts matched for both total collisions and individual birds ($r = 1.00$). To verify that video counts were repeatable, a second observer watched a random subset of 17 videos; they counted an equal number of birds in all cases ($r = 1.00$).

Emission spectra of the floodlight and coastal light sources were measured with an optical spectrometer (QE65000, Ocean Optics, Florida, USA) with a spectral range of 200–1,100 nm and a 3-nm resolution. Spectra from floodlights were measured at 3.5 m to match the distance the light source was from sheets

during experiments. Coastal light sources were measured on October 13, 2024, and were selected for measurement by (1) being visible from Bon Portage Island and (2) brightness. Because the distance between the spectrometer and light sources varied, emission curves were standardized by assigning emission values as fractions of the highest value. The amount of light reflecting off sheets was measured using a digital luxmeter (LYX1330B, Walfront Electronic, Hubei, China) with a 0.1-lux to 200,000-lux range ($\pm 5\%$ accuracy).

Statistical Analysis

All statistical analyses were conducted in R 4.3.2 (R Core Team 2023). Because the number of times each sheet was presented differed, statistical tests and graphs for comparing collisions between treatments use the number of individuals/collisions per 30-min sheet cycle. Statistical tests were run with data on how many individuals collided with sheets and how many total collisions were made with sheets. Although running tests using the number of total collisions may compromise independence assumptions, it is impossible to be sure that what was believed to be one individual colliding with a sheet twice was not actually 2 separate individuals. Mann-Whitney U tests were used to compare differences in collisions between light-on and light-off intervals. Due to the number of comparisons made between sheet colors and patterns, 6 Kruskal-Wallis U tests were performed for each category (front collisions by color, back collisions by color, and pattern collisions separated by individual and by total collisions) and sequential Bonferroni post-hoc tests were used to identify significantly different comparisons in a conservative manner (Rice 1989; see Rothman 1990, Nakagawa 2004).

To compare collisions between age classes, we categorized collisions as either before (June through August) or during (September and October) the fledging period. This does not guarantee that collisions during the fledging period were fledglings, but collisions before the fledging period were almost certainly adults, given the earliest fledge date on Bon Portage is September 1 (Pollet *et al.* 2021).

In 2024, a distinction was made between collisions with the front and the back of the sheets because of different thicknesses and thus different amounts of light passing through them. In 2025, all 3 sheets had identical thicknesses and collisions with the front and back were combined for statistical tests, but we report them separately for consistency.

To test for associations between environmental factors and collisions with sheets in 2024, nights were broken into 30-min intervals corresponding to the 30-min color cycles and assigned either 0 (no collisions) or 1 (≥ 1 collision). Wind speed, moon illumination, and temperature data were collected from the nearest coastal weather station, Baccaro Point, ~20 km from the study site (Environment Canada 2025). Weather data were reported hourly and each 30-min interval was matched to the closest hour's report. Likewise, cloud cover was measured every hour at the field site using the Okta scale (Smith *et al.* 2017) that was modified to include fog conditions as a 9 (light fog, moon or stars visible) or 10 (thick fog, no moon or stars visible). Precipitation data were not included because experiments were not performed on nights with rainfall to prevent compromising the birds' thermoregulation and the equipment. We attempted to reduce the number of environmental variables we tested for using a principal components analysis (PCA), but the first PC explained only 33% of the variation in those variables,

which was no better than a random expectation of 46%, based on the Broken Stick Model (Jackson 1993). Hence, we instead used a logistic regression that included all environmental variables, sequentially removing non-significant associations (Crawley 2005).

RESULTS

Observations on sheet colors were collected on 28 nights in 2024 for a collective 92.5 hr, and observations on sheet patterns

were collected on 12 nights in 2025 for a collective 34.5 hr. In 2024, a majority of 118 individual birds (156 total collisions) were counted prior to the fledging period (sample sizes in Table 2; Figure 3). The experiment was conducted solely before the fledging period in 2025 and included 56 individual birds (76 total collisions) (Figure 3).

In 2024, whether counting by the number of individuals or by total collisions, *H. leucorhous* were more likely to collide with either fronts or backs of sheets during light-on intervals (Tables 2 and 3). Collisions with the front of the sheets were

TABLE 2. Cumulative observations, medians (Q2), and interquartile ranges (IQR) of *Hydrobates leucorhous* collisions with the front and the back of the sheets suspended in a colony in Nova Scotia, Canada, compared among different light (2024), sheet color (2024), and sheet pattern (2025) treatments, and differentiated by individual birds and total collisions.

Treatment	<i>n</i>	Sheet front collisions						Sheet back collisions					
		By individual			By total collisions			By individual			By total collisions		
		Count	Q2	IQR	Count	Q2	IQR	Count	Q2	IQR	Count	Q2	IQR
Light on	184	75	0	0.25	100	0	1	33	0	0	45	0	0
Light off	184	8	0	0.00	9	0	0	2	0	0	2	0	0
White	67	38	0	1.00	56	0	1	26	0	1	31	0	1
Beige	52	24	0	0.00	24	0	1	14	0	0	14	0	0
Black	65	13	0	0.00	15	0	0	0	0	0	0	0	0
Plain	23	15	0	1.00	30	1	2	16	0	1	18	0	1
Grid	23	8	0	1.00	8	0	1	5	0	1	5	0	0
Stripes	23	5	0	0.00	5	0	0	6	0	0	9	0	0

n denotes the number of 30-min sheet color cycles for which data were collected.

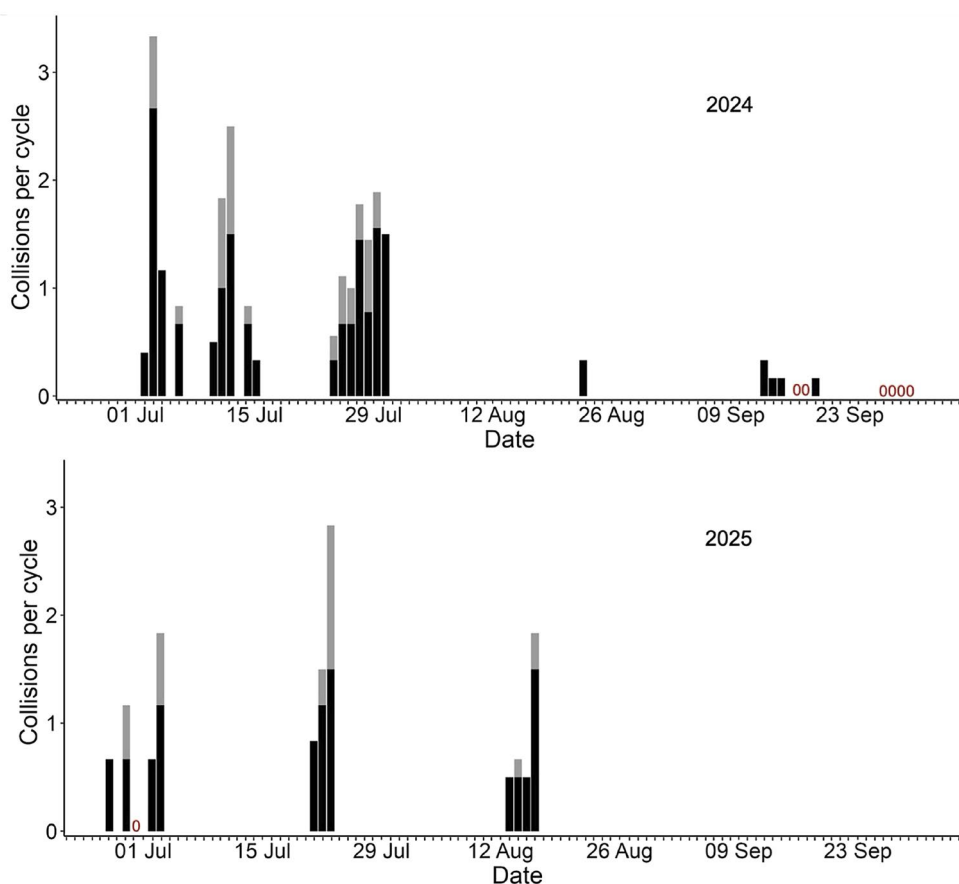


FIGURE 3. All *Hydrobates leucorhous* collisions with sheets (both fronts and backs) suspended in a colony in Nova Scotia, Canada, per 30-min color cycle differentiated by individual birds (black) and by total collisions (gray). Zeroes indicate nights sampled without any collisions observed.

TABLE 3. Mann–Whitney *U* tests comparing *Hydrobates leucorhous* collisions with sheets suspended in a colony in Nova Scotia, Canada between light-on and light-off conditions (sample sizes equal) categorized within 30-min sheet color or pattern cycles.

Comparison	Year	<i>n</i>	By individual		By total collisions	
			<i>U</i>	<i>P</i>	<i>U</i>	<i>P</i>
Sheet front light on vs. front light off	2024	184	20,468	<0.001*	20,910	<0.001*
Sheet back light on vs. back light off	2024	184	19,232	<0.001*	19,424	<0.001*
Sheet front light on vs. back light on	2024	184	18,843	0.007*	18,954	0.006*
Sheet front light off vs. back light off	2024	184	17,480	0.06	17,481	0.06
Patterned sheets light on vs. light off	2025	69	3,424	<0.001*	3,425	<0.001*

*Significant comparison at $P=0.05$.

statistically more likely than collisions with the back during light-on intervals and followed a similar pattern during light-off intervals, although the difference for light-off intervals was only suggestive (Table 3). In 2025, 55 birds collided with sheets during light-on intervals and only 1 occurred during light-off intervals (Table 3).

The only significant differences in collisions with fronts of colored sheets with the light on (Tables 2 and 4; Figure 4) were between white and black sheets, the former of which had more collisions, both by the number of individuals and by total collisions. Birds were statistically less likely to collide with the back of black than with the back of white or beige sheets during light-on intervals, both by individuals and by total collisions, but were only statistically more likely to collide with backs of white than beige sheets when counting by individuals (Tables 2 and 4; Figure 4).

Storm-petrels were significantly more likely to collide with the plain sheet than either of the patterned sheets when counting by total collisions, but were only more likely to collide with the striped sheet than the plain sheet when counting by individuals. Storm-petrels were equally likely to collide with both patterned sheets regardless of counting method (Tables 2 and 4; Figure 5). After sequential removal of non-significant associations between collisions and environmental variables (all $|Z| \leq 1.63$, all $P \geq 0.11$), only temperature remained significant (estimate = -0.71 ± 0.19 SE, $Z = -3.7$, $P < 0.001$).

Eighteen coastal locations with a total of 224 lights were visited, most of which were dock or street lights. Eleven locations were wharves with illuminated fishing vessels. Lights on fishing vessels were not included in counts, because many ships were not in port at the time of measurement. Emission spectra of 209 lights (93%) matched with standard white LED spectra, one (1%) matched with high pressure sodium spectra, and 14 (6%) were suspected to be fluorescent (Figure 6). Docked lobster boats were illuminated with at least one LED light each but may have used different types of lights while at sea.

TABLE 4. Kruskal–Wallis *U* tests with post hoc sequential Bonferroni tests with adjusted *P* value to compare *Hydrobates leucorhous* collisions with colored and patterned sheets suspended in a colony in Nova Scotia, Canada, broken into 30-min sheet color cycles during light-on intervals ($n=67$ white cycles, $n=65$ black cycles, $n=52$ beige cycles), and 30-min sheet pattern cycles during light-on intervals ($n=23$ plain, $n=23$ grid, $n=23$ vertical stripe).

Comparison	By individual		By total collisions	
	<i>U</i>	<i>P</i>	<i>U</i>	<i>P</i>
Front of colored sheets	6.2	0.04*	8.4	0.02*
Black vs. white		0.04*		0.01*
Black vs. beige		0.44		0.32
White vs. beige		0.44		0.32
Back of colored sheets	26.2	<0.001*	23.7	<0.001*
Black vs. white		<0.001*		<0.001*
Black vs. beige		0.01*		0.002*
White vs. beige		0.01*		0.06
Patterned sheets	7.4	0.03*	9.2	0.01*
Grid vs. plain		0.07		0.03*
Stripe vs. plain		0.05*		0.03*
Stripe vs. grid		0.66		0.73

*Significant comparison at $P=0.05$.

DISCUSSION

Illuminated structures likely affect fallout rates directly by increasing disorientation and likely increase risks of fatalities from various causes (Reed *et al.* 1985, Rodríguez *et al.* 2012, 2014, Ronconi *et al.* 2015). Our results suggest that darker or patterned vertical substrates may be a viable option to reduce collisions associated with ALAN by reducing reflected light. A white sheet, which had 2.7 times more bird collisions and 3.7 times more total collisions than a black sheet, also reflected almost 5 times more light than a black sheet. Higher luminosity may cause more collisions by increasing attraction of birds, as well as expanding the radius of attraction. The overall amount of reflected light was approximately equal for all 3 sheets in the pattern experiment. Gridded and vertically striped sheets, which had 2.4 and 2.8 times fewer bird collisions and 3.4 and 3.7 times fewer total collisions than a plain sheet, respectively, may have either offered a navigational landmark for birds to avoid, or by interrupting surface reflectivity, decreased attractive or disorienting effects.

Studies that have tested different methods of reducing procellariiform light attraction by making an area dimmer, such as decreasing light quantity, have had success at reducing fallout at coastal buildings (Reed *et al.* 1985, Burt 2022, Burt *et al.* 2024). Burt *et al.* (2024) reduced *H. leucorhous* fallout at a fish-processing plant by 57% by decreasing the number of lights by 75%. Our results suggest that if using less reflective wall colors or patterned walls is as successful at preventing collisions in practice as in a colony, it could have a similar effect on fallout (66% fewer bird collisions with a black than a white sheet and 58–65% fewer bird collisions with a patterned than a plain sheet) away from a colony, assuming that collisions are correlated with fallout.

Whether changing wall color or pattern could successfully reduce collisions at fallout locations that may be some distance from breeding colonies, such as described by Burt *et al.* (2024), remains untested. Our study was conducted in a colony where

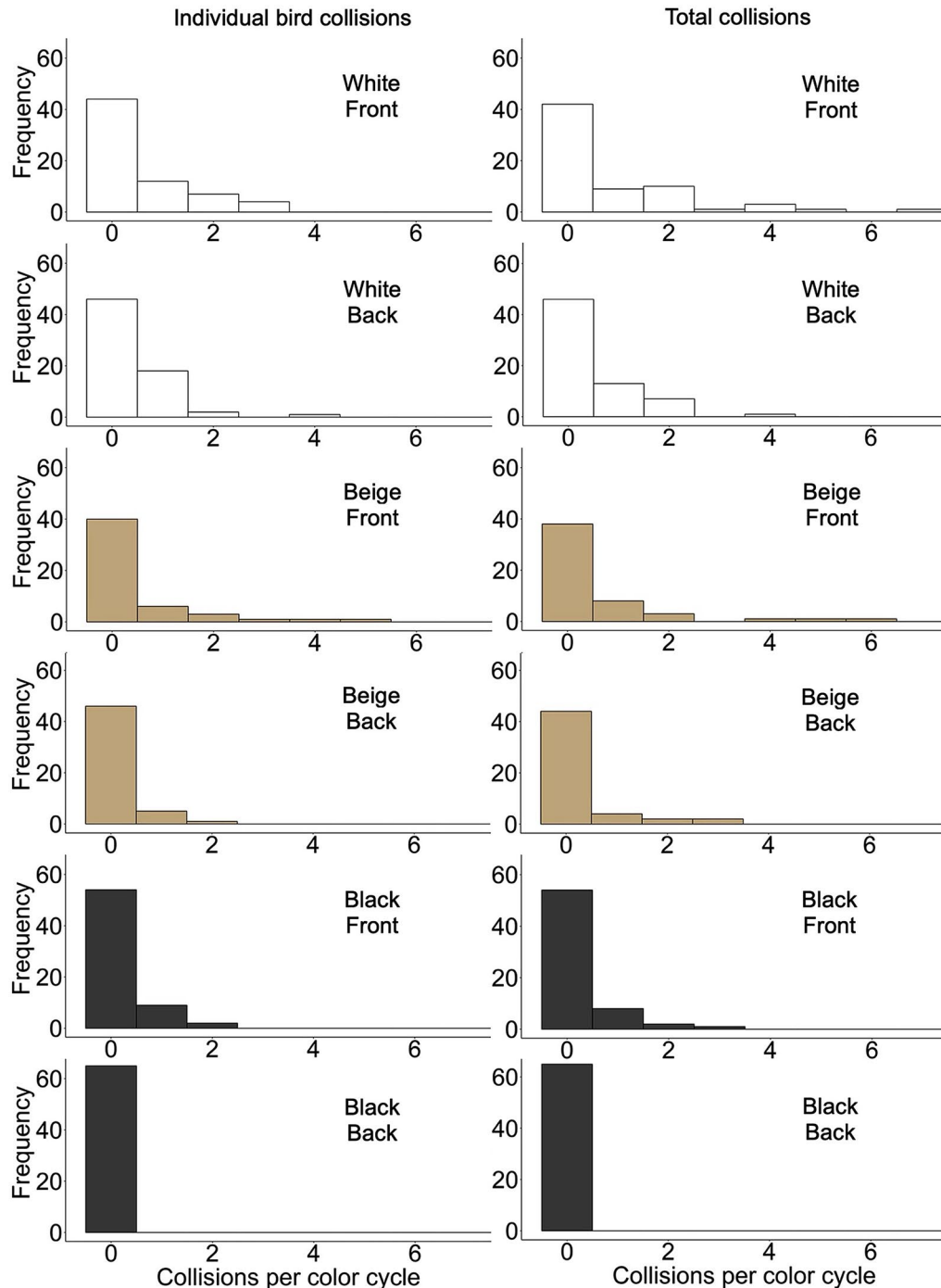


FIGURE 4. *Hydrobates leucorhous* collisions with fronts and backs of different sheet colors suspended in a colony in Nova Scotia, Canada during light-on intervals per 30-min cycle and showing counts by individual bird (left column) and by total collisions (right column).

H. leucorhous were already present, but ALAN often attracts procellariiforms at sea to coastal light sources (Rodríguez et al. 2014, Burt et al. 2024). Using darker wall colors may reduce attraction by dimming reflected light, but may have a stronger effect at reducing fallout by mitigating collisions once birds arrive at a light source. A patterned wall with increased light intensity will likely only have success preventing collisions, not preventing long-range attraction, because it does not reduce overall intensity of light sources. These methods may also have

success on fishing vessels or on fossil fuel platforms in flight paths between foraging sites and colonies.

One concern about the practicality of using darker wall colors at fallout sites is that ALAN is often for worker safety (Ronconi et al. 2015, Rodríguez et al. 2017a), which could be compromised by reducing reflected light. This might require facilities to compensate by increasing light intensity, which could be counterproductive at decreasing fallout. Testing if darker vertical substrate colors reduce collisions even if light

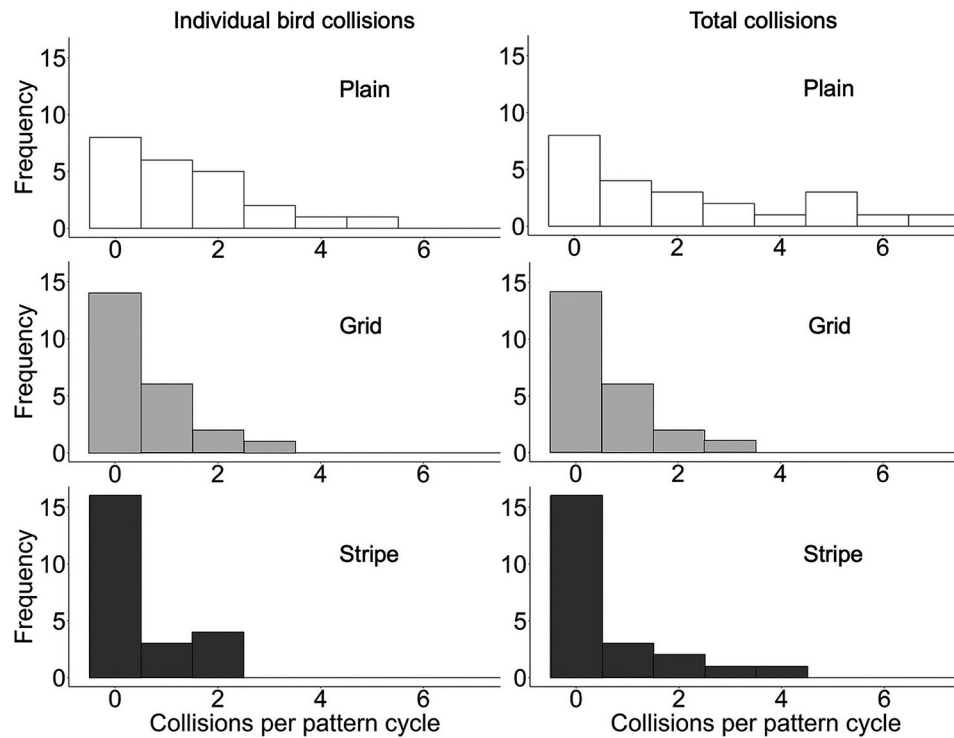


FIGURE 5. *Hydrobates leucorhous* collisions with fronts and backs (pooled) of different sheet patterns during light-on intervals per 30-min cycle and showing counts by individual bird (left column) and by total collisions (right column).

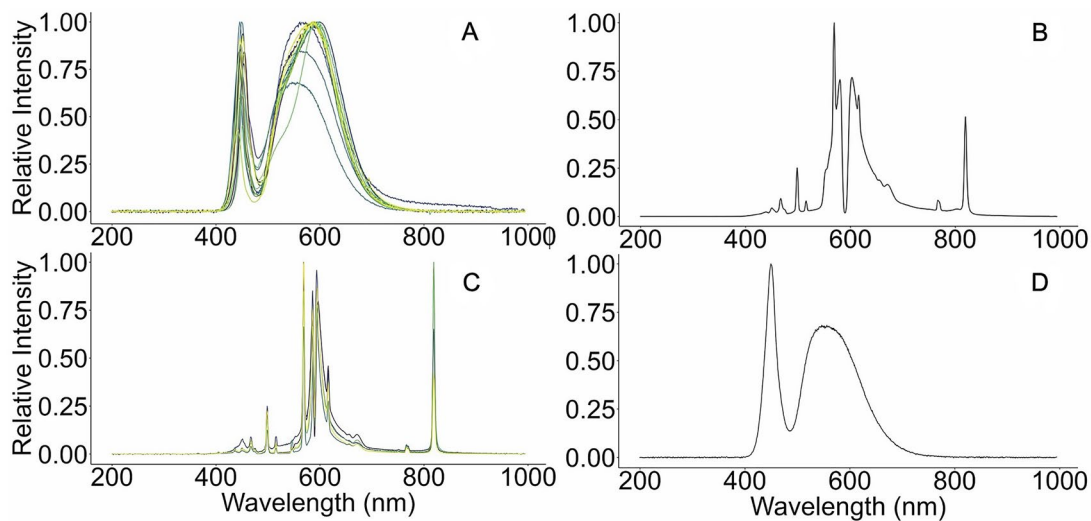


FIGURE 6. Emission spectra of (A) light-emitting diodes (LEDs), (B) a high-pressure sodium light, (C) suspected fluorescent lights, and (D) an LED light suspended from a docked lobster boat in Barrington Municipality, Nova Scotia, Canada adjusted to relative intensity.

intensity is increased could determine if this method is an option to balance human and bird safety. Using patterned walls, however, circumvents this issue because we observed fewer collisions with them than a plain white wall even if light intensity was approximately equal. Patterned walls may be a more realistic option in situations where light intensity cannot be safely decreased.

Causes of procellariiform light attraction are debated, but hypotheses generally fall into 2 categories: those that focus on attraction (Imber 1975, Rodríguez *et al.* 2017a) and those that

focus on disorientation (Reed *et al.* 1985, Telfer *et al.* 1987). Attraction-based hypotheses include confusion with bioluminescent prey, positive phototaxis of fledglings, and fledglings associating light with burrow entrances. However, no evidence of positive phototaxis has been found in nestlings of either *C. borealis* (Atchoi *et al.* 2023) or *H. leucorhous* (Hutchinson 2026), both of which are species of procellariiform, and although fallout affects mostly fledglings, adults do still strand (Gjerdrum *et al.* 2021, Burt *et al.* 2024). At least 94% of birds colliding with sheets in our study were adults, possibly because

colonies are less active in fall or fledglings may not fly much within colonies before leaving and therefore encounter sheets infrequently. Performing this experiment at a stranding site would likely yield a higher proportion of fledgling collisions, given the ratio of fledglings to adults at stranding sites (Gjerdrum *et al.* 2021, Burt *et al.* 2024). Regardless, high proportions of adult collisions suggest that explanations for light attraction need to include a mechanism for both adults and fledglings. Furthermore, fledgling fallout can also be explained by delayed eye development in burrow-nesting species (Archoi *et al.* 2020) or inexperience, because fledglings do not receive parental care after fledging and are therefore unable to learn navigational skills from their parents (Pollet *et al.* 2021).

Hypotheses proposing that ALAN causes disorientation include interference with magnetic field receptors or celestial cues used for navigation. Light-sensitive cryptochrome magnetoreception could explain ALAN disorientation and be used in colonies to adjust headings relative to the ground (Guilford *et al.* 2019), but no evidence of magnetoreception has been found in procellariiforms (Gagliardo *et al.* 2013, Pollonara *et al.* 2015, Syposz *et al.* 2020). Celestial navigation could also explain ALAN disorientation; it works well at large spatial scales and may explain why fallout increases on overcast nights. This could also be explained by clouds amplifying ALAN intensity (Kyba *et al.* 2011), however, and does not explain why fallout increases on new moon nights, when stars are more visible (Gjerdrum *et al.* 2021, Burt *et al.* 2024). The moon itself could be a navigation cue, but this is considered unlikely by some because its position changes more rapidly than does that of stars (Zolotareva and Chernetsov 2021) and no relation between fledge date and moon phase has been found (Miles *et al.* 2010, Rodríguez *et al.* 2023). A more likely explanation for effects of low moon illumination on fallout is that ALAN appears brighter in comparison, when the moon is absent (Reed *et al.* 1985).

Procellariiform fallout may be explained by a combination of attraction and disorientation. For example, Rodríguez *et al.* (2015) noted that fledglings on their first flights appeared to show light attraction but on their second flights had higher tortuosity, indicating disorientation. Disorientation alone does not explain why birds strand at light sources away from flight paths (Burt 2022, Burt *et al.* 2024). It is also important to consider that mechanisms by which ALAN diverts birds from their flight paths (navigation) may not be the same mechanisms causing collisions (obstacle avoidance). Brown *et al.* (2022) suggested that long- and short-range attraction deserve separate hypotheses. Our results support the suggestion that short-range effects of ALAN are disorientation. Although we did not regularly count storm-petrels flying overhead during different light intervals, we observed more individuals flying overhead during light-off intervals. A casual count on July 12, 2024, estimated over 150 birds overhead during a light-off interval. When the light was turned on, birds scattered quickly and only a few dozen were observed. This pattern held during every interval on every night and has been observed in other light attraction studies in colonies (Syposz *et al.* 2021, Hutchinson 2026). Despite fewer birds being overhead during light-on intervals, collisions with illuminated sheets were 9.4 times more likely than collisions with unilluminated sheets in 2024. Furthermore, we observed birds colliding with other objects in the area before or after colliding with sheets, but rarely did they collide with the light itself. This was also reported by Guilford *et al.* (2019),

where birds collided with a building but not often with illuminated windows. The inverse relationship between numbers of birds in the air and numbers of collisions suggests that birds are more capable of avoiding sheets when lights are off than when lights are on and that *H. leucorhous* adults are repelled by ALAN, although this may be different for fledglings. Applying disorientation hypotheses to object avoidance reveals different concerns. Celestial navigation may be affected by ALAN, but it seems unlikely to affect object avoidance or be employed during local flights within colonies. Magnetic interference could make sense if ALAN was interfering with cryptochrome receptors in the eye that detect magnetic fields. Even if birds navigated by a different mechanism, such as olfaction, cryptochrome receptors could still be active and responding to ALAN, causing disorientation. A third and often unconsidered hypothesis is dazzling (i.e. when light overwhelms photoreceptors, a known effect of ALAN on insects; Owens and Lewis 2018). ALAN may not interfere directly with navigational cues but may be bright enough to disrupt vision and cause disorientation during low-visibility flight (Guilford *et al.* 2019).

The significance of temperature in relation to collision rate is likely an artefact of more activity during summer than during fall and probably does not suggest an actual influence. The lack of significant effects of other environmental factors could indicate that they have no effect on collisions, at least within colonies, or that a longer sampling period with more unique weather would be required to reveal patterns (e.g. the number of clear nights was much lower than the number of cloudy nights). Other factors such as time of night and time of year likely affected collision rates more because of changing colony activity levels.

Despite concerns about increased LED use, how LEDs affect procellariiform light attraction is understudied. Current research suggests LED lighting is about equally attractive as high-pressure sodium lights but significantly less attractive than metal halide lights at colonies (Rodríguez *et al.* 2017b, Urmston *et al.* 2022). In our study, over 90% of coastal lights at potential fallout locations near Bon Portage were LEDs. Further research on how light type affects fallout, at fallout sites and not just at colonies, is needed to evaluate threats of LEDs to procellariiforms.

Sheet colors used in this study were selected to maximize contrasts in reflected light and to resemble wall colors in local communities. Certain colors of equal reflectivity, such as green or red, for example, could influence *H. leucorhous* collisions without jeopardizing worker safety. To our knowledge, there has only been one brief mention of changing wall color successfully reducing avian collisions with structures (Wang *et al.* 2011).

Reducing reflected light by changing wall colors or patterns could have applications for other groups of organisms, such as nocturnally migrating passerines and sea turtle hatchlings (Wang *et al.* 2011, Nichols *et al.* 2018). Hatchling turtles orient from their beach nests toward the ocean following star and moon reflections, but urban developments along tropical beaches make land brighter than the ocean, causing hatchlings to orient in the wrong direction (Tuxbury and Salmon 2005). Walls of illuminated structures along known turtle-nesting beaches could be repainted in darker shades.

To conclude, a black vertical substrate reduced individual *H. leucorhous* collisions by 66% compared to a white vertical substrate, likely due to a reduction in reflected light, and

patterned vertical substrates reduced individual bird collisions by 58–65% compared to a plain vertical substrate. Using less reflective wall colors or patterned walls therefore has promise at reducing procellariiform fatalities by mitigating collisions and potentially decreasing overall fallout. Future studies should focus on applying this method at fallout sites and effects of using less reflective surfaces at commercial facilities to assess risks to human safety. *Hydrobates leucorhous* were also 9 times more likely to collide with a sheet when it was illuminated than when it was dark despite birds flying overhead being repelled by the light, suggesting that effects of ALAN at close ranges involve disorientation, not attraction.

Supplementary material

Supplementary material is available at *Ornithological Applications* online.

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Ethics statement

All field procedures were completed after being approved by the Acadia Animal Care Committee (protocol #04–25).

Conflict of interest statement

The authors declare no conflicts of interest.

Author contributions

D.S. and A.R. conceived the idea and D.S. and M.R. supervised research; A.R. with assistance from L.H. performed the experiments; A.R. wrote the paper with edits from D.S., M.R., and L.H.; A.R. designed the experiment with inputs from D.S., M.R., and L.H.; A.R. analyzed the data. D.S., M.R., and A.R. contributed materials and funding.

Data availability

The datasets generated during and/or analyzed during the current study are available in the [Supplementary Material](#).

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