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Authors: Foss, Carol R., Ronning, Donald J., and Merker, David A.

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RESEARCH ARTICLE

Intense short-wavelength light triggers avoidance response by Red-tailed Hawks: A new tool for raptor diversion?

Carol R. Foss,[1]* **Donald J. Ronning,**[2] **and David A. Merker**[3]

[1] Audubon Society of New Hampshire, Concord, New Hampshire, USA
[2] Lite Enterprises, Nashua, New Hampshire, USA
[3] Cape May Raptor Banding Project, Hanover, New Hampshire, USA
* Corresponding author: cfoss@nhaudubon.org

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ABSTRACT

Collisions between birds and aircraft present serious safety and economic risks to aviation worldwide. Research into the potential for lighting to reduce collision risk has been evolving since the mid-twentieth century. Our objective was to explore the potential for using customized light-emitting diodes (LEDs) as a deterrent to wild raptors under natural conditions. The Red-tailed Hawk (*Buteo jamaicensis*) is among the top 10 bird species struck by aircraft in the United States; these collisions have resulted in aircraft damage, emergency landings, aborted takeoffs, and human injuries and fatalities. We tested the reactions of migrating Red-tailed Hawks to pulsing, high-brightness, monochromatic LEDs that targeted the avian photoreceptors for light of short and extremely short wavelengths. We installed 3 lighting units to illuminate 2 lures at a raptor banding station during the peak of Red-tailed Hawk migration and compared the number of captures and aborted approaches to these lures with captures and aborted approaches at a control station. The proportion of Red-tailed Hawks that aborted their approaches to lures at the treatment station was >5 times that of hawks that aborted approaches at the control site. We observed individuals abruptly changing flight direction as they neared the illuminated lures. Our results suggest that, with further testing and refinement, high-brightness, monochromatic LEDs that specifically target avian photoreceptors could provide a useful tool to divert raptors from hazardous situations.

Keywords: raptor deterrent, monochromatic LEDs, bird strikes, airports

La luz intensa de longitud de onda corta desencadena la respuesta de escape de *Buteo jamaicensis*: ¿Una nueva herramienta para el desvío de rapaces?

RESUMEN

Las colisiones entres aves y aeronaves representan un riesgo serio en seguridad y en términos económico para la aviación en todo el mundo. La investigación sobre el potencial de la iluminación para reducir los riesgos de colisión ha estado evolucionando desde mediados del siglo veinte. Nuestro objetivo fue explorar el potencial de uso de diodos emisores de luz (LEDs por sus siglas en inglés) personalizados como elementos disuasorios para las rapaces silvestres en condiciones naturales. *Buteo jamaicensis* está en la lista de las diez especies de aves más golpeadas por aeronaves en los Estados Unidos; estas colisiones han ocasionado daños a las aeronaves, aterrizajes de emergencia, despegues abortados y lesiones y fatalidades humanas. Evaluamos la reacción de individuos migratorios de *B. jamaicensis* a LEDs titilantes monocromáticas de alto brillo que tienen como objetivo los foto-receptores de luz de longitud de onda corta y extremadamente corta de las aves. Instalamos tres unidades de luz para iluminar dos señuelos en una estación de anillado de rapaces durante el pico de la migración de *B. jamaicensis* y comparamos el número de capturas y de aproximaciones abortadas a estos señuelos con las capturas y las aproximaciones abortadas a una estación control. La proporción de individuos de *B. jamaicensis* que abortó sus aproximaciones a los señuelos en una estación con el tratamiento fue cinco veces mayor que la de los individuos que abortaron en el sitio control. Observamos individuos que cambiaron abruptamente sus direcciones de vuelo a medida que se aproximaron a los señuelos iluminados. Nuestros resultados sugieren que con más evaluaciones y refinamiento, los LEDs monocromáticos de alto brillo que específicamente se centran en los foto-receptores de las aves pueden brindar una herramienta útil para desviar a las rapaces de situaciones peligrosas.

Palabras clave: aeropuertos, choques de aves, disuasión de rapaces, LEDs monocromáticas

INTRODUCTION

Humans have attempted to reduce conflicts with birds since ancient civilizations erected scarecrows to repel birds from crops. Bird-deterrent technology has evolved to include both visual and auditory approaches, and applications now encompass protecting birds from anthropogenic hazards as well as protecting human investments from birds. Uses have expanded well beyond agricultural environs to include settings such as water supplies, landfills, toxic waste sites, oil spills, and airfields (e.g., Read 1999, Transport Canada 2002, Williams et al. 2013).

Much of the recent bird deterrence research has focused on strategies for preventing collisions between aircraft and birds (bird strikes), which have long constituted serious safety and economic risks (Transport Canada 2002, Airport Cooperative Research Program 2011, Desoky 2014). Although bird strikes in the United States have involved more than 500 avian species, collisions with waterfowl, gulls, and raptors are the most likely to cause serious damage (Dolbeer et al. 2015). The Red-tailed Hawk (*Buteo jamaicensis*) was the 8th most common species among identified birds struck by civil aircraft in the United States during 1990–2014; of 2,038 Red-tailed Hawk strikes during this period, 298 caused damage to the aircraft, 213 caused a negative effect such as an emergency landing or aborted takeoff, 8 resulted in human injuries, and 1 caused 8 human fatalities. These incidents resulted in 13,278 hr of downtime and US$23,649,229 in reported costs (Dolbeer et al. 2015). From 1990 through 2014, 41% of reported bird strikes occurred while planes were on the ground, 31% happened when planes were within 152 m above ground level (AGL), and 25% took place when planes were between 153 m and 1,676 m AGL; the highest strike occurred at 9,540 m AGL (Dolbeer et al. 2015).

The potential for using light to repel birds has become an active area of research within the last 50 yr. Using radar to assess flight behavior, Larkin et al. (1975) found that the majority of nocturnally migrating birds attempted to avoid searchlight beams and small aircraft landing lights at distances of 200–600 m. Subsequent research on avian responses to light has occurred during daylight (Lustick 1973, Blackwell et al. 2002, 2012, Blackwell and Bernhardt 2004).

Blackwell and Bernhardt (2004) tested the responses of penned Brown-headed Cowbirds (*Molothrus ater*), European Starlings (*Sturnus vulgaris*), Herring Gulls (*Larus argentatus*), and Mourning Doves (*Zenaida macroura*) to the approach of pulsing 250 W white aircraft landing lights mounted on a ground-based vehicle. Cowbirds yielded inconsistent results, while the other species showed no differences in their responses to treatments and controls. Lustick (1973) investigated the effects of high-intensity lasers on European Starlings, Mallards (*Anas platyrhynchos*), and gulls (*Larus* spp.). Although birds consistently avoided a concentrated laser beam, such a beam can damage the human eye and requires careful use by a human operator. Blackwell et al. (2002) reviewed the effectiveness of newer, safer lasers for dispersing flocks of various species and found that results differed among species and situations (i.e. urban vs. rural) and ranged from no reaction to effective dispersal.

More recently, researchers have attempted to increase the distance at which aircraft are visible to birds. Blackwell et al. (2012) found that captive, wing-clipped Canada Geese (*Branta canadensis*) reacted more quickly to approaching fixed-wing, radio-controlled aircraft fitted with 2 "white" LED lights than to unilluminated aircraft.

It is well established that birds can see colors of shorter wavelengths than humans, including portions of the violet and ultraviolet spectra (e.g., Bennett and Cuthill 1994, Ödeen and Håstad 2003, Aidala et al. 2012). The recent development of LEDs has generated new opportunities for investigating the perception of these wavelengths by different avian taxa. Most research on avian short-wavelength vision has focused on foraging behavior (e.g., Härmä et al. 2011, Lind et al. 2013) and breeding biology (e.g., Bennett et al. 1997, Hunt et al. 2003). Doppler et al. (2015) were the first to experiment with short-wavelength light as an avian deterrent. Using the Brown-headed Cowbird as a test species, they modeled the spectra of 5 commercially available monochromatic LEDs (470–635 nm) and determined that the lowest wavelength, 470 nm (blue) light, provided the highest chromatic contrast for the species' visual system. They then exposed captive cowbirds to pulsed and continuous 470 nm light mounted on stationary and overflying radio-controlled aircraft, and showed that operation of the lights affected the timing of alert responses in some situations.

Color vision in birds is enabled by 4 types of single-cone photoreceptors within the retina, providing perception of a broad color spectrum. These cone receptors are sensitive to extremely short wavelengths (UVS/VS), short wavelengths (SWS), medium wavelengths (MWS), and long wavelengths (LWS), respectively, and each cone type contains corresponding visual pigments that help to determine the cone's spectral absorbance (Hart 2001, Lind and Kelber 2009). Visual pigments differ among species, creating differences in peak sensitivity. The UVS/VS cone pigments exhibit peak absorption at 362–426 nm (ultraviolet to blue light), and peak absorption for the SWS cone pigments is at 430–463 nm (blue light); there is considerable overlap in the frequencies absorbed by these cones (Hart 2001).

The objective of this study was to determine whether high-intensity short-wavelength light could deter wild, free-flying raptors from approaching a potential food source. Specifically, we examined the relative frequency of

Red-tailed Hawk captures and aborted approaches to illuminated vs. unlit lures at a test and a control raptor banding station during fall migration. We predicted a priori that the combination of high brightness and a wavelength that targeted specific cone cells would overwhelm the visual system of exposed birds and trigger an instinctive avoidance reaction.

METHODS

We tested the reactions of Red-tailed Hawks to high-brightness, monochromatic LEDs at an established raptor banding station on Cape May Point, New Jersey, USA, for 7 consecutive days from November 9 to 15, 2014. We chose the Red-tailed Hawk for our study because of its history of involvement in damaging bird strikes and its common occurrence at raptor migration banding sites. Raptor researchers have been capturing and banding migrating hawks on Cape May Point since 1967. The Cape May Raptor Banding Project provided an opportunity to attempt to alter the behavior of migrating Red-tailed Hawks attracted to lures at a banding station. The peak of Red-tailed Hawk fall migration in northeastern North America typically occurs in early November (Bildstein et al. 2008), the period when we focused our collection of data. Since 2000, strong Red-tailed Hawk flights (>150 individuals counted on a single day) have typically occurred at the Cape May Point Hawkwatch site (approximately 3.0 km southwest of our treatment station) during the second week of November (HMANA 2016).

The treatment station was located in an open field approximately 1.5 km east of Delaware Bay and 3.0 km north of the Atlantic Ocean. A control station was located approximately 2.4 km to the southwest and was surrounded by a dense growth of shrubs and low trees. Each banding station consisted of a mowed grassy area of ~0.2 ha that contained a wooden blind and 5 traps designed for raptors of various sizes. Cape May banding stations were set up in identical configurations, including orientation (facing northeast), types and locations of traps, and types and locations of lure birds. For Red-tailed Hawks and other large species, tethered Rock Pigeons (*Columba livia*) served as lures for manually operated bow nets at 2 lure poles in each banding station. Experienced raptor banders used standard procedures to attract migrating raptors to the lures (Bloom et al. 2007:199).

Red-tailed Hawks, and raptors in general, are within the group of birds that have UVS/VS cones with peak spectral sensitivity in the range of 403–426 nm (Hart et al. 1999, Ödeen and Håstad 2003). While no peak spectral sensitivity data are available specifically for Red-tailed Hawks, calculated values for 5 other raptor species of 4 genera were 405 or 406 nm (Ödeen and Håstad 2003). We selected a light wavelength to maximize visibility to raptors and minimize visibility to humans within the range of currently available LEDs. Minimizing human visibility increases the potential application of this technology in settings where flashing lights could pose a safety hazard (e.g., aircraft and airports) or an aesthetic issue (e.g., ridgetop wind energy facilities). At the time of our study, 445 nm was the shortest obtainable wavelength for commercially available LEDs.

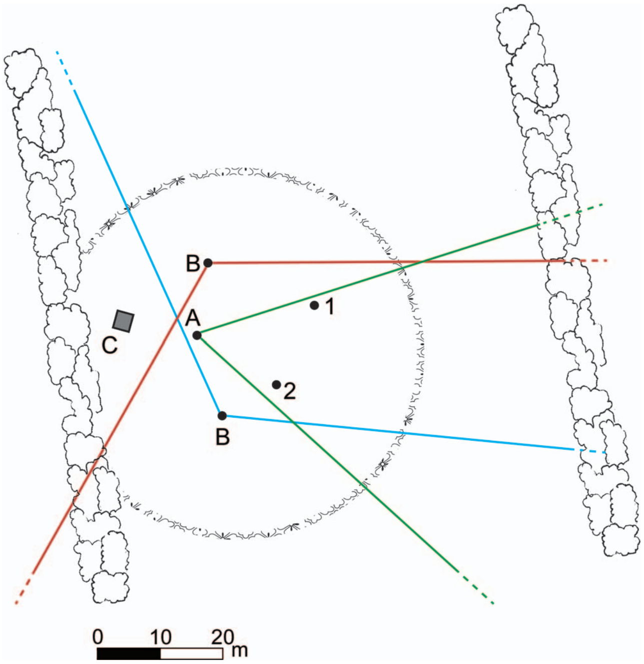

FIGURE 1. Layout of light treatments at the Cape May Point banding station, New Jersey, USA, used to test the reactions of Red-tailed Hawks to high-brightness, monochromatic LEDs: A = 900 W LED unit in 3 × 3 array (see also Figure 2); B = 1,000 W LED unit in 1-over-1 configuration (lines illustrate full width at half maximum light beam thresholds); and C = station blind. The numerals 1 and 2 indicate the lure poles. Diagram by Dyanna Smith.

We installed 3 custom-fabricated lighting units at the treatment station, each positioned approximately 1 m above the ground, angled at approximately 30° above horizontal, and directed to illuminate the lure poles (Figure 1). Two units consisted of 2 445 nm, 500 W LEDs mounted 1 above the other, each with a Gaussian-shaped beam and full width at half maximum (FWHM) of ± 60°. These lights produced a calculated peak intensity of 4.8×10^{-7} W per cm^2 at 100 m distance and were programmed to pulse at 2 Hz with an on–off time of 250 ms–250 ms. The third unit consisted of 9 445 nm, 100 W LEDs arranged in a 3 × 3 array, each with a Gaussian-shaped beam and FWHM of ± 30° (Figure 2). These lights produced a calculated peak intensity of 7.1×10^{-7} W per cm^2 at 100 m distance and were programmed to pulse at a rate of 1.5 Hz with an on–off time of 250 ms–500 ms.

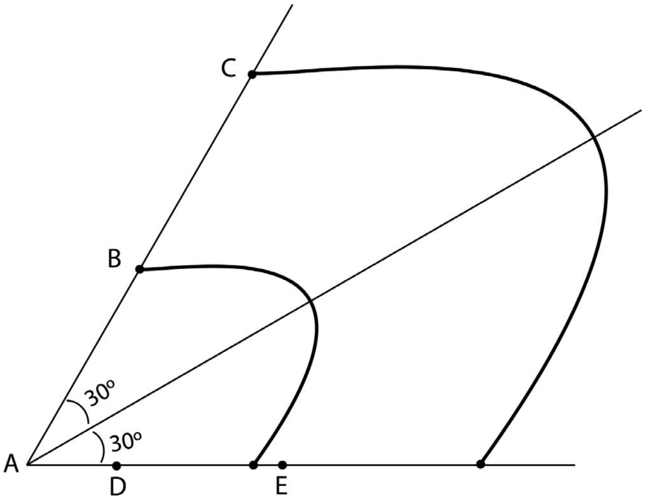

FIGURE 2. Two-dimensional depiction of full width at half maximum light beam intensity profile for the 900 W 3 × 3 array of high-brightness, monochromatic LEDs used to test the reactions of Red-tailed Hawks to intense single-wavelength light: A = Light source; B = 50 m from light source; arc illustrates peak intensity of 2.8×10^{-6} W per cm^2; C = 100 m from light source; arc illustrates peak intensity of 7.1×10^{-7} W per cm^2; D = lure pole 1; and E = hedgerow. Diagram by Dyanna Smith.

The 100 W and 500 W LED multichip packages were fabricated from commercial-grade LED die using wire-bonding and surface-mount technology. Each 100 W LED package was assembled with a focusing lens to focus the light into a narrow beam; no focusing lenses were included in the 500 W packages. The LED packages were mounted on aluminum plates to dissipate the waste heat that they generated. A small, single-board computer (Raspberry Pi; Raspberry Pi Foundation, Cambridge, UK) programmed in C provided 3-V transistor-transistor logic (TTL) control signals to multiple DC relays, which enabled each LED package to switch on and off independently with 1-millisecond precision. Multiple off-the-shelf AC/DC power converters independently powered each 100 W and 500 W LED package. A portable 120-V AC generator provided power to the system. The generator was located along a hedgerow ~100 m downhill from the equipment and was surrounded by 2.54-cm (1-inch) thick foam sheets to muffle sound.

Lights at the treatment station were activated throughout station operation, ~0900 to ~1600 hours. We installed a nonoperational, imitation 3 × 3 lighting array in the same position with respect to lures at the control station. Observers documented all Red-tailed Hawks that followed a direct flight path toward the banding station, and recorded the outcome as "capture" when an individual held fast to a lure or as "abort" when an individual suddenly veered away within 5–20 m of a lure.

Prior to the experiment, we tested whether there were inherent differences between the control and treatment banding stations due to uncontrolled effects (e.g., wind currents, surrounding land use) that might bias our test results. We used a chi-square contingency test on weekly Red-tailed Hawk capture data for 2010 through 2013 to test for independence between station (control vs. treatment) and year.

During 1 week in 2014 (November 9–15), we activated light units at the treatment station and recorded the numbers of Red-tailed Hawks that were attracted to lures at control and treatment stations. We tabulated the numbers of hawks that were captured and those that approached but actively avoided the lures (i.e. aborted their approach) at each station. We conducted 2 chi-square contingency tests to assess the effects of the lights. We used weekly Red-tailed Hawk captures at the control and treatment stations to test for independence between station type and experiment status (i.e. the 3 weeks preceding the experiment vs. the week of the experiment), and used individual Red-tailed Hawk captures and aborts (response) to test for independence between response and site. All statistical analyses were conducted in SYSTAT 13 (Systat Software, San Jose, California, USA).

RESULTS

During the 2010–2013 banding seasons, total Red-tailed Hawk captures at the treatment banding station exceeded those at the control station ($\chi^2_3 = 8.74$, $P = 0.03$; Table 1). Thus, prior to our experiment, we expected Red-tailed Hawk activity at the treatment station to at least be comparable with activity at the control station. During the 2014 banding season, Red-tailed Hawk captures at the treatment station were nearly 4 times those at the control station during the 3 weeks before the experiment, but captures at the control station were >2 times the number at the treatment station during the test week ($\chi^2_1 = 33.46$, $P < 0.001$; Table 2). Observers documented a total of 134 Red-tailed Hawks at the 2 banding stations during the test week. Of the individuals documented, 31 were captured and 23 aborted their approach at the treatment station, whereas 74 were captured and 6 aborted their approach at the control station. The abort-to-capture ratio was much higher at the treatment station (0.74) than at the control station (0.08; $\chi^2_1 = 23.41$, $P < 0.001$).

Red-tailed Hawks that approached the lures at the treatment station reacted to the light field in multiple ways. Those that aborted their approaches followed 4 general behavior patterns: (1) Birds that were approaching the banding station on a low flight path at an elevation well below the top of the light field abruptly turned away from the lures, curved back behind the blind, and left the area (Figure 3A); (2) Birds that were approaching along a high

TABLE 1. Numbers of Red-tailed Hawks captured during fall migration in 2010–2013 at banding stations on Cape May Point, New Jersey, USA, subsequently used to test behavioral responses to high-brightness, monochromatic LEDs. Treatment = banding station at which experimental LEDs were deployed in 2014, and Control = banding station without experimental illumination. The percentages of the total number of hawks caught at the treatment station each year are shown in parentheses.

	Treatment	Control	Total
2010	33 (72%)	13	46
2011	29 (74%)	10	39
2012	104 (67%)	52	156
2013	31 (50%)	31	62
Total	197 (65%)	106	303

TABLE 2. Numbers of Red-tailed Hawks captured at 2 Cape May Point, New Jersey, USA, raptor banding stations in 2014 during 3 weeks prior to (weeks 9–11) and the week of an experiment (week 12) to test behavioral responses to high-brightness, monochromatic LEDs. No lights were operating at either banding station during weeks 9–11 (October 19–November 8); lights were operating at the treatment station but not at the control station during week 12 (November 9–16). The percentages of the total number of hawks caught at the treatment station each week are shown in parentheses.

	Treatment	Control	Total
Week 9	18 (82%)	4	22
Week 10	8 (80%)	2	10
Week 11	29 (78%)	8	37
Week 12	31 (30%)	74	105
Total	86 (49%)	88	174

flight path approached the lures from above, descended to ~35–65 m above the ground, then abruptly rose again, moved a few meters forward, and repeated the behavior, in some cases several times, before leaving the area (Figure 3B); (3) Birds approaching rapidly through a gap in the hedgerow abruptly pulled up vertically before reaching the lures (Figure 3C); and (4) some birds perched in a hedgerow within 50 m of the lures but beyond the strongest influence of the lights for varying periods of time before eventually leaving the area without approaching the lure.

Of the 31 birds captured at the treatment station, 29 initially followed the flight path described in (1) above, but then flew over the blind toward a lure with the lights at their backs (Figure 3D). The other 2 perched in a hedgerow, peering at the lures periodically from behind limbs and foliage, before swooping rapidly over to a lure.

DISCUSSION

Recent experiments with birds and lights (e.g., Blackwell and Bernhardt 2004, Blackwell et al. 2012, Doppler et al. 2015) have assessed the reactions of birds in fenced enclosures to lights mounted on stationary and moving vehicles. Our study differed by using stationary light sources and wild, free-flying birds. This design enabled us to document actual avoidance behavior.

Aborted approaches are a regular, though infrequent, occurrence during normal banding operations. Movement within the blind, visibility of a lure line (extending between a lure bird's harness and the blind), sudden movement or vocalization from a lure, and distraction by another bird are the most frequent triggers of an aborted approach to a lure. Individuals approaching a lure on a direct course horizontally or stooping from above would not typically abort their approach. Standard data collected at banding stations does not include aborted approaches. However, the experienced banders with whom we worked considered the proportion of aborted approaches at the control site to be typical for Red-tailed Hawks at Cape May Point. During any banding season, a small percentage of individuals perch at a distance from the lures before making their next move, and roughly half of these birds eventually pursue a lure.

Abortive behaviors were more common at our light treatment than at the control site. Experimental light significantly altered the foraging behavior of migrating hawks, resulting in either temporarily or completely aborted attempts to depredate the lure birds. If we assume that the 0.08 abort rate at the control site is "normal," 4 aborted approaches would have occurred at the treatment site regardless of the lights. Also, considering the 2 individuals that were not deterred, we can estimate that the lights in some way affected 89% of Red-tailed Hawks that directly approached lures at the treatment banding station. Of the 54 individuals that approached the station, 23 (43%) abruptly changed their flight paths and left the area; of the 31 individuals that were captured, 94% altered their original flight paths to approach a lure with the light sources behind them. Two Cooper's Hawks (*Accipiter cooperii*) and 2 Northern Harriers (*Circus cyaneus*) that approached the lures during our study reacted in a similar manner to Red-tailed Hawks, abruptly veering away from a lure after entering the light field. These reactions are consistent with the observations of Larkin et al. (1975) that the majority of nocturnally migrating passerines abruptly turned away from a "white" searchlight beam in the only other study involving wild, free-flying birds.

Hunger is a powerful motivator, and the ability of our lights to turn raptors away from potential food is strong testimony to their deterrence potential. Although it is not possible to attribute the observed behaviors to any particular stimulus, veteran banders (D. Merker, L. Reitsma) working at the station had not previously witnessed the abrupt turn or abrupt rise behaviors,

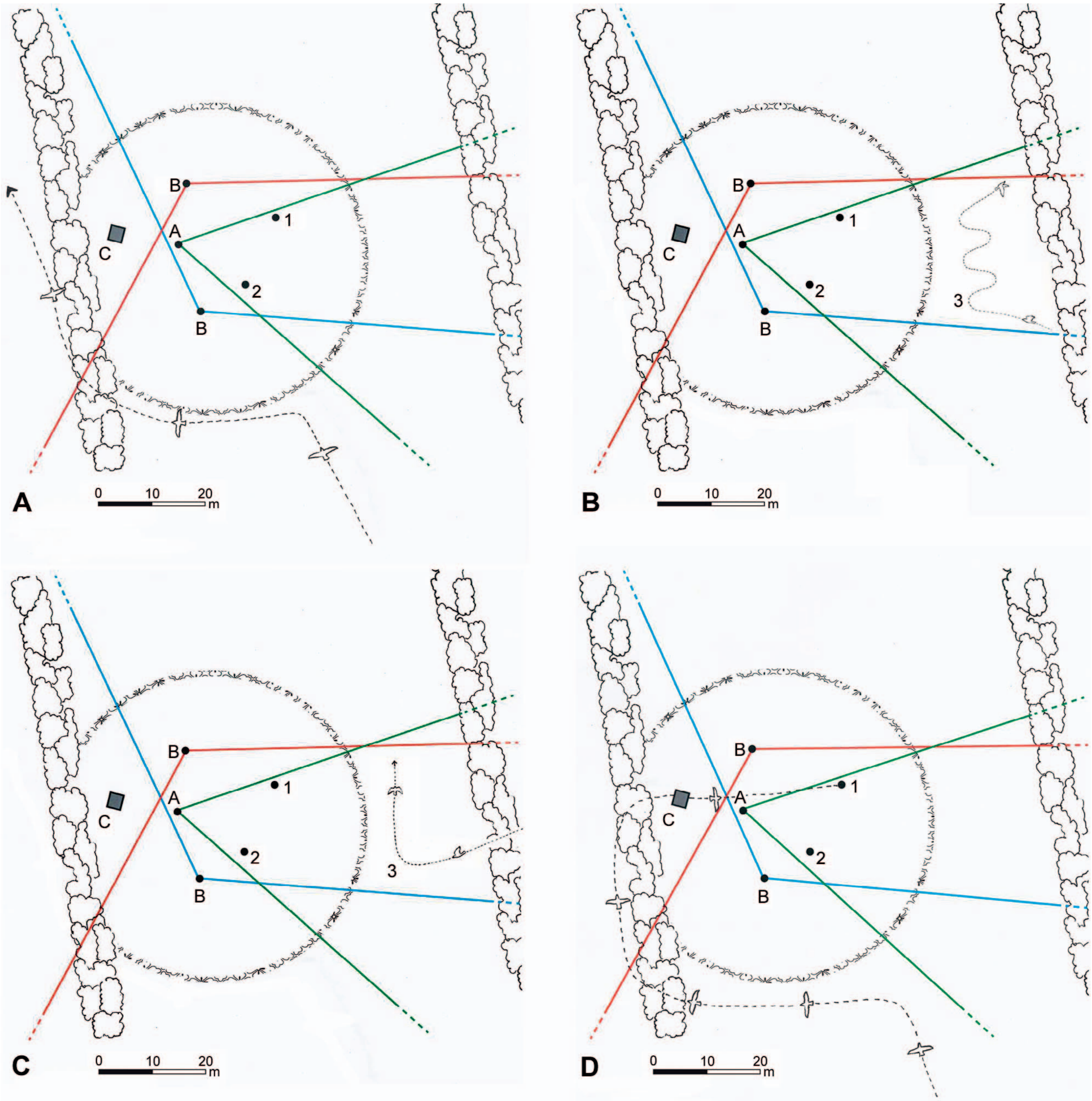

FIGURE 3. Flight paths of Red-tailed Hawks on encountering a high-brightness, monochromatic LED light field at a Cape May Point banding station, New Jersey, USA: A = 900 W LED unit in 3 × 3 array (see also Figure 2); B = 1,000 W LED unit in 1-over-1 configuration (lines illustrate full width at half maximum light beam thresholds); and C = station blind. The numerals 1 and 2 indicate the lure poles. (A)–(C) illustrate flight paths of birds that aborted their approach to a lure: (**A**) Low approach from side; (**B**) High approach from side; the numeral 3 indicates a horizontal depiction of a vertically undulating flight path, with troughs approximately 18 m above ground level (AGL) and peaks approximately 36 m AGL; (**C**) Rapid approach through hedgerow; the numeral 3 indicates a horizontal depiction of a flight path abruptly changing from horizontal to vertical. (**D**) Flight paths of captured Red-tailed Hawks on encountering the high-brightness, monochromatic LED light field, approaching the lure with lights at back. Illustrations by Dyanna Smith and Charlotte Harding.

suggesting that these were responses to the lights. It is impossible to know whether physiological differences or behavioral accommodations conferred higher tolerance for the lights on the 2 undeterred individuals.

Inexplicably, the number of Red-tailed Hawk captures at the control station during the week of our experiment exceeded historical numbers of this species captured in a 1-week period for the 2 sites combined. There were no intrinsic reasons to have expected more Red-tailed Hawks at the control banding station than at the treatment station. On the contrary, the extensive open fields immediately surrounding the treatment station provided more attractive foraging habitat for Red-tailed Hawks than the dense woody vegetation surrounding the control station. The treatment station is known among Cape May banders as the best banding station for Red-tailed Hawks, and our analysis of historical data confirmed that impression.

We did not have the capacity to determine distances and altitudes at which Red-tailed Hawks reacted to the lights other than by ocular estimation. However, we can derive some general conclusions based on light intensities and their calculated attenuation at the relative distances where hawks responded. Our observations suggested that 445 nm light at intensities less than $\sim1\text{–}2 \times 10^{-6}$ W per cm^2 may have been visible to approaching raptors, but triggered no obvious behavioral response. Between 1–2 and $\sim4\text{–}8 \times 10^{-6}$ W per cm^2, the light appeared to irritate individuals with only casual interest in the lures sufficiently to deter them from approaching further. Other individuals, perhaps those more intent on their prey, were not deterred and continued to approach the lure. However, at $\sim4\text{–}8 \times 10^{-6}$ W per cm^2, the light intensity appeared to effectively blind the individual, which turned abruptly to avoid the light. The effect is analogous to the solar glare or solar glint experienced by humans, which essentially overwhelms the visual system and renders the subject temporarily blind. At relatively close range, this system triggered an instantaneous, instinctive avoidance reaction. Nearly all individuals that were captured at the test station had circled around and approached a lure with the lights at their backs, avoiding the blinding effect.

An important feature of our design was the ability to target a specific area of the avian visual spectrum while minimizing visibility to the human eye. Light of wavelengths less than 420 nm is considered to be undetectable by humans (CIE 1976). Human observers could only detect illumination from the 445 nm LEDs under certain conditions. Illumination of nearby objects was invisible to humans in sunlight and was barely visible on the grass in front of the units under heavily overcast conditions and toward dusk. The lights were visible looking directly at the LEDs. We activated the lights one night in full darkness, which provided an impression of what the hawks might have experienced during the day. The LEDs lit up an extensive area, well beyond the limits of the banding station, and clearly illuminated the hedgerow $\geq$50 m beyond the units.

Conservation Applications

LED technology continues to evolve, with improvements in stability, operating life, and flux density. As monochromatic LEDs in additional wavelengths become available at lower costs, opportunities to develop custom devices for avian deterrence will expand. Future research should investigate avian reaction distances to lights of specific wavelengths and intensities, and should perhaps incorporate radio-controlled aircraft to assess reactions of free-flying birds to approaching lights when no attractant (potential prey) is involved. The results of this study support the value of future investigations in this area.

We propose that high-brightness LEDs beyond the normal sensitivity of human vision but visible to the avian eye could provide an effective bird deterrence tool in diverse situations. This technology could be adapted to reduce bird strikes during takeoff, landing, and direct flight. At airfields, lights could be positioned to illuminate an avoidance zone along runways and approach paths. Lights could also be mounted on aircraft to reduce bird strikes beyond the immediate airport environment. This technology could additionally be adapted to reduce avian mortality at toxic settling ponds, multistory buildings, commercial-scale solar arrays, and wind energy facilities. Mobile units could be deployed to create avoidance zones at oil spills and other temporarily hazardous locations. Units could also be installed on cell towers and other communications facilities to deter raptor nesting activity. We believe that, with further testing and refinement, high-brightness, monochromatic LEDs can become an important addition to the bird deterrence toolbox.

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Ethics statement: Care of lure birds and banding procedures conformed to the *Guidelines to the Use of Wild Birds in Research*.

Author contributions: D.J.R. conceived, designed, fabricated, and operated the LED devices, contributed to writing the paper, and reviewed drafts; C.R.F. developed the field methods, collected the test station field data, analyzed the data, and wrote the paper; and D.A.M. ran the treatment banding station.

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