High-intensity urban light installation dramatically alters nocturnal bird migration

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Billions of nocturnally migrating birds move through increasingly photopolluted skies, relying on cues for navigation and orientation that artificial light at night (ALAN) can impair. However, no studies have quantified avian responses to powerful ground-based light sources in urban areas. We studied effects of ALAN on migrating birds by monitoring the beams of the National September 11 Memorial & Museum’s “Tribute in Light” in New York, quantifying behavioral responses with radar and acoustic sensors and modeling disorientation and attraction with simulations. This single light source induced significant behavioral alterations in birds, even in good visibility conditions, in this heavily photopolluted environment, and to altitudes up to 4 km. We estimate that the installation influenced >1.1 million birds during our study period of 7 d over 7 y. When the installation was illuminated, birds aggregated in high densities, decreased flight speeds, followed circular flight paths, and vocalized frequently. Simulations revealed a high degree of probability and subsequent attraction for nearby birds, and bird densities near the installation exceeded magnitudes 20 times greater than surrounding baseline densities during each year’s observations. However, behavioral disruptions disappeared when lights were extinguished, suggesting that selective removal of light during nights with substantial bird migration is a viable strategy for minimizing potentially fatal interactions among ALAN, structures, and birds. Our results also highlight the value of additional studies describing behavioral patterns of nocturnally migrating birds in powerful lights in urban areas as well as conservation implications for such lighting installations.

Significance

Artificial light at night is a novel stimulus in the evolutionary history of nocturnal animals. Light pollution can significantly alter these organisms’ behaviors, from migration to foraging to vocal communication. Nocturnally migrating birds are particularly susceptible to artificial light because of adaptations and requirements for navigating and orienting in darkness. However, light’s effects on in-flight behaviors have not been well quantified, especially in urbanized environments. Here we report that an iconic urban light installation dramatically altered multiple behaviors of nocturnally migrating birds—but these effects disappeared when lights were extinguished. We recommend selective removal of light pollution during nights with substantial bird migration to mitigate negative effects on birds, in particular collisions with lighted structures.

Author contributions: A.F. developed the study, collected visual observations and weather data, and wrote the paper; B.M.V.D. shaped the study, performed statistical analysis, and contributed to writing the paper; K.G.H. analyzed radar data and contributed to writing the paper; B.M.V.D. and K.G.H. generated figures and animations; A.M.D. developed simulations and produced associated figures and text; H.K. performed acoustic energy analysis; H.K. and A.F. analyzed acoustic data; S.B.E. provided bird mortality data, provided coordination, support, and access to the study site. The authors declare no conflict of interest.

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Data deposition: All visual counts made at Tribute in Light are archived in the eBird database at ebird.org/ebird/hotspots/1744278.

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behaviors in clear sky conditions (but see ref. 48) and urbanized (e.g., heavily photopolluted) environments. Understanding the disruptive effects of short-term ALAN (e.g., lighting installations, sporting events) on nocturnal bird migration in urbanized and photopolluted areas and identifying the extents of these effects in clear sky conditions are important conservation priorities.

We took advantage of a unique opportunity to quantify birds’ responses to ALAN by monitoring numbers, flight patterns, and vocalizations of birds aloft during alternating periods of illumination and darkness in the powerful light beams of the National September 11 Memorial & Museum’s (NSMM’s) “Tribute in Light” (TiL) in New York, NY (Fig. 1). Baseline densities, we estimate that the installation and the number expected in that area given installation under clear sky conditions during periods of illumination. We detected large aggregations of circling birds above the installation using data from the KOKX Brookhaven, NY WSR-88D radar station, revealing how numbers of birds and their rates of passage changed in the presence or absence of illumination. Second, we measured birds’ vocal activity by recording their in-flight vocalizations, or flight calls, from the base of the installation. Increased flight calling activity in nocturnally migrating birds may indicate disorienting or confusing conditions (30, 32). If nocturnally migrating birds were attracted to and disoriented by the lights, we expected to observe higher densities of birds flying at slower flight speeds and vocalizing more frequently during periods of illumination. Finally, we used a flow model to simulate bird behaviors in ALAN conditions for comparison with observed radar data. These spatiotemporal distribution simulations investigated three important behavioral parameters to explain bird concentrations at the installation: the probability that the lights affected nearby birds, the distance over which the lights affected birds, and whether disoriented birds showed preferred flight directions toward the display. Together, these parameters determined how long birds remained in the illuminated area.

Results

We detected large aggregations of circling birds above the installation under clear sky conditions during periods of illumination (Figs. 1 A and C and 2, Movies S1–S3, and SI Appendix, Fig. S1). By summing the differences between bird numbers within 5 km of the installation and the number expected in that area given baseline densities, we estimate that 1.1 million birds (95% CI: 0.6–1.6 million) were affected by this single light source during our study period of seven nights over 7 y (SI Appendix, Fig. S2). The numbers of birds affected varied by year, in part due to variation in the magnitude of migratory passage through the surrounding area on the study night (SI Appendix, Fig. S3), but all years showed strong increases in bird density with decreasing distance to the light source (Fig. 3 and SI Appendix, Fig. S4). Under illumination, peak bird densities near the installation reached magnitudes 20 times greater than the surrounding baseline during all 7 y (SI Appendix, Fig. S5A), where we defined baseline as the mean density in the area 2–20 km from the site. Peak bird densities exceeded 60 times baseline in 5 of the 7 y and 150 times baseline in 3 y (2008, 2012, and 2013), but peak densities never exceeded 13 times baseline in the absence of illumination (SI Appendix, Fig. S5A). Vocal activity beneath the lights was intense during periods of aggregation (Fig. 2C and SI Appendix, Fig. S6). Bird densities, flight speeds, and vocal activities all varied closely with illumination (Fig. 2). Removal of illumination resulted in rapid changes in nocturnal migration behaviors, with birds dispersing, increasing flight speeds, decreasing calling activity, and moving away from the site in a matter of minutes (Fig. 3 C and D).

We found a strong effect of illumination on the maximum standardized peak bird density and the maximum number of birds detected within 500 m of the installation during each period of darkness and adjacent periods of illumination. Considering the 0.5° radar elevation angle, maximum standardized bird densities were 14 times greater when the light display was illuminated (t = 5.70, P < 0.0001). Maximum bird numbers averaged 3.4 times greater during lit periods (t = 3.89, P = 0.0003). Remarkably, these effects were also present at high altitudes (1.5° radar elevation angle, sampling altitudes of 2.4–4.1 km): maximum standardized densities increased on average by 3.9 times (t = 3.25, P = 0.002) and maximum bird numbers by 3.3 times (t = 2.34, P = 0.023) during lit periods at high altitudes. We note that we did not detect many birds congregating in the beams during 2014; this year was not included in the above analyses because the lights were not shut down. We observed a strong effect of light on bird behavior during all other years (SI Appendix, Fig. S7).

Considering all radar observations, total numbers of birds within 500 m of the installation averaged 3.4 times higher during illuminated periods (t = 9.34, P < 0.0001). Standardized peak densities showed a similar pattern (factor = 6.4 times, t = 3.72, P = 0.0003), with the effect strengthened to 46 times higher during illuminated periods in 2015 (t = 2.91, P = 0.004). Again,
Discussion

This study quantifies ALAN-induced changes in multiple behaviors of nocturnally migrating birds. Our data show that the light installation strongly concentrates and disorients migrants flying over a heavily urbanized area, influencing ≈1.1 million birds during seven nights over 7 y.

Existing published accounts report attraction to lights almost exclusively under poor-visibility conditions (45, 53), but our results show alterations to migrants’ behaviors in clear and mostly clear conditions. These effects were also significant in the high altitude 1.5° radar data (total numbers: factor = 1.9 times, t = 3.49, P = 0.0006; standardized peak density: factor = 4 times, t = 4.00, P < 0.0001). Radial velocities were significantly lower during illuminated periods (main effect = −1.7 m s⁻¹, t = −2.10, P = 0.037), especially during 2012 (effect with interaction = −5.4 m/s, t = −2.38, P = 0.02) and 2015 (effect with interaction = −4.3 m/s, t = −2.52, P = 0.01). Flight call rates recorded beneath the installation were significantly higher during illuminated periods (main effect = 1.4 times, t = 4.53, P < 0.0001), especially in 2015 (factor with interaction = 2.9 times, t = 6.88, P < 0.0001); the effect was reduced in 2013 (factor with interaction = 1.1 times, t = −2.30, P = 0.02). Because our model of vocal activity included bird density as a predictor to account for variation in calling explained by the sheer quantity of birds, the significant increases in calling with illumination can be attributed primarily to behavioral differences.

Simulation results showed that birds were highly likely to become disoriented as they approached the installation (SI Appendix, Fig. S8). The model matching radar observations most closely (model 1; Fig. 4 and SI Appendix, Tables S1 and S2) had disorientation probability α = 0.95, indicating a very high likelihood of disorientation near ALAN, and the characteristic disorientation distance (σ) was 1,500 m. The concentrations of birds observed at the installation could only be explained by including directed flight toward ALAN for disoriented birds (concentration parameter κ > 0; best model κ = 0.1). In contrast, simulated birds diffused easily away from ALAN when assuming a nondirectional random walk (κ = 0; model 3 in SI Appendix, Table S1). These results support our visual observations of birds circling around the installation and arc indicative of light attraction.

The stabilization time to a steady-state increased with disorientation probability (α) and flight directionality toward ALAN (κ) (Fig. 4, Movies S4–S8, and SI Appendix, Table S1). The stabilization time provides information on the residence time of birds in the beam, as a steady state is only reached over time periods longer than the average residence time. Our model 1, which is conservative in this regard, predicts a stabilization time of 34 min. We note that this is the result of average behavior for all birds contributing to the density pattern, and individual residence times may be considerably longer or shorter. Our simulation provides a theoretical framework for explaining our visual and remotely sensed observations, underscoring that the light installation attracted and entrained passage migrants.

Finally, direct visual observations showed that birds frequently circled the installation during periods of illumination and decreased speed on approach to the installation (SI Appendix). Such observations also highlighted a particular hazard that nocturnally migrating birds face in urbanized areas with ALAN: collisions with structures. Observers noted in 2015 and 2016 that many birds collided with the glass windows of a building under construction just north of the lights (50 West Street; Fig. 1A). The full extent of mortality was not clear, primarily because of challenges surveying nearby sites, scaffolding preventing birds from falling to ground level, and removal of carcasses by scavengers and building staff. We therefore do not have sufficient data to analyze mortality with respect to illumination and migration intensity. However, existing data are archived in the New York City Audubon D-Bird database (https://d-bird.org/).

Fig. 2. Time series of radar and acoustic measures of Tribute in Light impact on migratory birds. Observations (in Coordinated Universal Time) from September 11–12, 2015 of (A) migration activity within 500 m of the installation, (B) radial velocity within 500 m of the installation, and (C) vocal activity during periods of TiL illumination. D–F show corresponding data with and without illumination. Density increase factor (D) is defined as the peak bird density near the installation divided by the mean density 2–20 km away.

Fig. 3. Spatial and temporal influence of Tribute in Light on migratory birds. Migration activity (Left column) and radial velocity (Right column) at the installation pooled across years by distance from the study site (A and B) and activity as a function of time since TiL shutdown (C and D). To account for year-to-year variation, migration activity was normalized across years using a z-score standardization (values minus the nightly mean, divided by the nightly SD). Illumination represented by green and periods without illumination by gray. C and D include only measures ≤500 m from the installation. Data fit with generalized additive models (A and B: bs = “cs,” m = 2, k = 10; C and D: bs = “ds,” m = 2, k = 5) and weighted by migration activity for radial velocity models. Shading represents 95% confidence intervals.
Further controlled experiments in field and laboratory settings would help determine the causes of attraction and disorientation at local and landscape scales. Studies that varied light intensity locally found that birds respond more strongly with more intense light (61–63). Sampling bird migration at and near light installations of varying intensities may provide additional opportunities to study attraction and disorientation. There are few vertically pointing light installations of comparable intensity in the United States (e.g., Luxor, Las Vegas, NV), but many structures use similarly powerful horizontal lights (e.g., sports stadia, construction sites, offshore oil rigs). Studies at such locations have not used multimodal remote sensing to quantify disruptions but have noted behavioral changes similar to those that we observed (e.g., aggregation, circling, and increased vocal activity) (57, 64).

Studies of ALAN are revealing large-scale effects on bird behavior that range from flight alterations to changes in stopover habitat use. There is mounting evidence that migratory bird populations are more likely to occur in urban areas during migration, especially in the autumn (65). Light pollution may explain this relationship, as recent research suggests that birds associate with higher levels of ALAN during migration (66). Given alarming declines in migratory bird populations (67, 68), these studies highlight the importance of understanding ALAN’s implications for migratory bird populations.

Finally, our study highlights a model relationship for collaboration among diverse stakeholders. A hallmark of this project was frequent and public cooperation among the NSMM, the Municipal Arts Society, New York City Audubon, the Cornell Lab of Ornithology, and stakeholders with direct interest and responsibility for this event, all of whom acknowledged its potential to negatively impact birds. All parties agreed to keep the display illuminated unless potentially hazardous conditions for birds necessitated a short-term shutdown of the lights. Whereas discontinuing the display would be best for nocturnally migrating birds, such a scenario may not be possible at this time. TiL is arguably one of the world’s most iconic and emotional displays of light. The fact that the event’s organizers and participants were willing to periodically shut down the lights for the benefit of migratory birds is an encouraging acknowledgment of the importance of bird conservation. Moreover, despite occasional confusion and frustration among the tribute’s viewers, media coverage often highlighted a unified message from stakeholders about balancing potential hazards to migrating birds with the intent and spirit of the display.

**Methods**

During our 7-y study period, the tribute lights were shut down a total of 22 times, for >20 min each. This allowed us to directly contrast birds’ behaviors during adjacent dark and illuminated periods. We note that this study was opportunistic and not a controlled experiment. Furthermore, we note that such an opportunistic approach results in some inevitable challenges in interpretation, for example because we were unable to control for additional factors that could influence the degree to which birds congregate at light sources. Such factors likely include wind speed, wind direction, temperature, cloud cover, and ground-based sources of light and sound. However, because ambient conditions were generally similar within each night, we can still readily measure the additive effect of illumination on bird behavior, given each year’s suite of conditions.

**Study Site and Scope.** TiL is an event held annually since 2002 on September 11th to memorialize lives lost during the terrorist attacks of September 11th, 2001 (www.911memorial.org/tribute-light). NSMM currently operates the light installation atop a parking garage near the site of the former World Trade Center in New York City (NYC), NY at the southern end of Manhattan Island (40.707°, −74.015°).

Massive nocturnal migratory movements of birds regularly occur over our study area during mid-September (12, 13, 69, 70). However, since the timing of these movements depends on local and regional weather and wind conditions (71–74), the magnitude of migratory passage on the single night of September 11th varies greatly among years. An agreement between New York City government, New York City Audubon, the City University of New York, the Massachusetts Audubon Society, and the New York State Department of Environmental Conservation enabled us to conduct simultaneous migratory bird counts in the New York metropolitan area from 2002 to 2008 (69, 70).

**Data Collection.** The light installation at TiL is operational from dusk on September 11th to 6 a.m., which includes the greatest number of birds passing over the study area to the south. Data were collected at 30-min intervals to capture diurnal activity patterns associated with the light installation (39, 41, 42, 55, 58). The local daytime artificial light source was the light from TiL (61, 62). At other times, birds were exposed to multifaceted sources of light and sound, including the artificial lights and sounds at TiL, natural light and sound from the New York City skyline, and natural light and sound from the surrounding landscape.

**Light Measurement Equipment.** Light intensity was measured using a portable digital photometer (model 9400; General Tools, New York City). The meter measured light intensity using a photodiode array placed 10 cm from the light source. The meter was periodically calibrated using a standard light source (model LR-1; General Tools, New York City).

**Data Analysis.** We used the lmer function from the lme4 package of R (75) to fit linear mixed-effects models on bird density per 30-min period. We quantified bird density using the following equation:

$$
\text{Density} = \frac{\text{Number of Birds}}{\text{Time (30 min)}}
$$

We applied a mixed-effects model with fixed effects of study period and light on bird density, and random effects of date and study period. We fitted five models (Table S1) using the Akaike information criterion (AIC) to assess model fit:

$$
\log(\text{Density}) = a + b \times \text{Lights on (mins)}
$$

where $a$ and $b$ are the model parameters, and $\text{Lights on (mins)}$ is the exposure to artificial light. We used the $R^2$ values from the model fits to indicate the proportion of variation explained by the model ($\text{R}^2 = 0.95$, $\text{R}^2 = 0.90$, $\text{R}^2 = 0.85$, $\text{R}^2 = 0.80$, $\text{R}^2 = 0.75$).

We conducted a paired-sample t-test to assess differences in bird density before and during the light installation at TiL. We defined adjacent dark and illuminated periods starting and ending 30 min before and after the light installation on September 11th. We included birds counted within 30 min before and after each light on trajectory to account for potential effects of artificial light on bird behavior during the 30-min period before and after the light installation.

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**Conflict of Interest.** None declared.
York City Audubon (NYCA) and NYSMM governs when to initiate the shutdown procedures: when numbers of birds circling in the beams exceed 1,000 individuals, based on visual observations. NYCA requests that lights be extinguished for ≥20 min. These requests originate from observers on site that are directly monitoring birds and their behaviors in the beams.

We examined September 11th nights from 2008 to 2016. High-resolution radar imagery did not exist before 2008, which limited our temporal scope. We excluded 2009 and 2011 because of the presence of precipitation, which interferes with analysis of radar data containing bird migration information. Of the remaining 7, migration conditions varied from marginal to favorable, assessed based on prevailing atmospheric conditions. Of these 7 y, the lights were shut down at least once during 5 of them; as a result, many of our analyses are restricted to these 5 y (2010, 2012, 2013, 2015, and 2016). Of the remaining 2 y, the first (2008) occurred before stakeholders could reach a consensus on a protocol for shutting down the light installation when birds were present and in danger. Organizers did not shut down the installation in 2014 because few birds were present in the lights.

Local Weather Conditions. We downloaded hourly local climatic data (LCD) for September 11 and 12, 2008–2016 (excluding 2009 and 2011 as described above) from the closest official National Weather Service station to the installation between evening and morning civil twilight (sun angle 6° below the horizon) (2010 and 2013) or (a) Nagra ARES-BB+ (2010 and 2013) or (b) a custom-built passive acoustic recording system (2015 and 2016), comprising a Raspberry Pi 2 Model B (Raspberry Pi Foundation) with a Cirrus Logic Raspberry Pi audio card (Cirrus Logic). We focused analysis on the 6- to 9-kHz frequency band to minimize interference from anthropogenic, geophysical, and nonavian biophonic noise and because many of the migrating birds in the New York City area emit flight calls in this frequency band (81). The microphone sensitivity in the relevant frequency band for this study (6–9 kHz) was −33 dB re 1 V Pa−1 (±2 dB).

Visual Observations. We complemented remote sensing data that characterized behaviors of nocturnally migrating birds above the installation with visual observations. Numerous observers, including one pair of us (A.F.) and others from NYCA and the local birdwatching community, made visual counts of nocturnally migrating birds at the installation during the period between civil twilight dusk and dawn. All visual counts are archived in the eBird reference database (ref; ebird.org/ebird/hotspots/L474278).

Statistics. We used generalized additive models (R package mgcv) (82) to quantify the effects of TIL illumination on birds’ behaviors (SI Appendix). We tested the categorical factors of light (on/off) and year on four metrics: standardized peak density, the total number of birds present within 500 m of the installation, the radial velocities of birds above the installation, and the number of flight calls recorded beneath the site. For models of time series, we also included smooth terms that accounted for overall variation in densities and behavior through the night. We confirmed that there was negligible temporal autocorrelation of residuals using the acf function in R for all analyses involving time series (SI Appendix). We log-transformed response variables when necessary to reduce residual skewness; for models with log-transformed response variables, we express effect size as a multiplicative factor, found by exponentiating the coefficient. Finally, to determine whether the light effects we present in the study are representative of those observed across years, we compared standardized peak densities across the lighted periods of all 7 y, including the 2 during which no light shutdowns occurred.

Simulations. To understand the dynamic patterns of bird density at the installation, we formulated a spatiotemporal flow model to simulate behavioral changes resulting from exposure to light. In our simulation, birds could transition between two behavioral states: an undisturbed migratory state and a disoriented state induced by TIL. Detailed methodology of our simulations is in SI Appendix.

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