

Spatiotemporal effects of artificial lighting on migratory birds

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Abstract

Nowadays artificial light can be found almost anywhere, but from an ecological perspective it is a relatively new phenomenon. The brightening of what used to be dark environments comes with significant consequences to the natural world. Internal biological rhythms are of substantial importance to the adaptation and thus survival of species. This literature review explores the topic of artificial light at night on migratory birds. The artificial light disrupts internal circadian and circannual rhythms used, among other things, to control timing of migration. This disruption leads to a desynchrony between avian migration timing and peaks in food abundance and optimal nesting times, leading to suboptimal fitness in migratory birds. In addition, phototaxis is very strong in migratory birds. Artificial lights blind and distract birds during migration, causing collisions, disorientation, and exhaustion responsible for millions of deaths each year. Many things can be done to reduce avian mortality due to artificial light, such as dimming or turning off lights, changing colours and wavelengths of the emitted light, or directing light at areas where it is most needed. Implementing these relatively simple measures sooner rather than later may contribute significantly to the conservation of avian species.

Introduction

To most of us, brightly lit cities are the norm, but from an ecological standpoint, artificial light at night (ALAN) is a relatively new phenomenon. Though campfires, candles and oil lamps have been around for a long time, the explosive increase in the use of artificial light started in the 1870s, when the first commercial lightbulb was invented. Nowadays we use this light to increase visibility, safety, and comfort, or perhaps to send signals to vehicles in the form of traffic lights, lighthouses, and aircraft warning lights. Sometimes we use lights simply to highlight statues and buildings for aesthetic purposes. However, with all the benefits it provides to humans come some significant caveats.

In the late 19th century, some early studies were done on the effects of light on the environment, but the awareness regarding this issue was barely present in the scientific community until the 1950s. In 1981 Verheijen introduced the term photopollution to describe artificial light with negative effects on animals and ecosystems. Ecosystems may experience photopollution directly from the artificial lights or indirectly, through sky glow. Large areas of the earth now experience light that differs from the natural regime in timing, intensity, and spectrum (Gaston *et al.*, 2013; Gaston *et al.*, 2015). More than a quarter of the land on earth is affected by ALAN and more than 80% of the world's human population lives in a brightened environment (Falchi *et al.*, 2016). In Europe and North America, the portion of the human

population exposed to ALAN approaches 99%. In addition, land area experiencing direct emissions from photopollution is estimated to be expanding by roughly 2% per year, with already lit areas increasing in brightness at a similar rate (Kyba *et al.*, 2017).

Research overwhelmingly shows that this increasing use of ALAN has negative effects on populations of birds, especially species that migrate at night. This literature review will explore the topic of photopollution, describing the effects ALAN has on migratory birds and their fitness. It focuses on the effects of ALAN on migration timing through disruption of the biological clock, and migration direction through the disruptive effects of phototaxis. The article concludes by proposing several methods to mitigate avian mortality due to artificial lighting.

Biological Clocks

Nearly all organisms, from cyanobacteria to humans, have evolved molecular biological clocks to adapt to rhythmic changes in the environment (Bell-Pedersen *et al.*, 2005). Through millions of years of evolution organisms have adapted to the rhythmic cycle of day and night as well as the moon and seasonal cycles. The circadian (*circa* = *approximately*; *dian* = *a day*) clock is an internal biological clock that functions autonomously with a cycle of approximately 24 hours (Bell-Pedersen *et al.*, 2005). Currently, almost every species relies on its circadian rhythm to synchronize its activities to the day-night cycle (Saini R *et al.*, 2019). An organism's internal clock influences nearly every biological process, including the rest/activity cycle, food intake, flowering, vertical and horizontal migration, growth, reproduction and more (Falcon *et al.*, 2020). Light is by far the most influential factor known to be capable of changing the timing of a biological clock. Photoperiod synchronizes the circadian rhythm and thus all the mechanisms that depend on them. As a result, changes in the natural daylight cycle affect nearly every organism on this planet, making it a very important topic for biologists and conservationists to investigate. The rapid employment of ALAN disrupts the natural light cycle by increasing brightness in the nighttime, which comes with big ecological consequences. Examples of the impact of ALAN are the extension of foraging and sexual competition of diurnal animals into the night (Titulaer *et al.*, 2012), and improved prey detection and predator avoidance (Roth & Kelber, 2004). Other studies showed that ALAN affects the ability of organisms to navigate around their environment at night (Somanathan *et al.*, 2008; van Langevelde *et al.*, 2011).

In mammals, the circadian system is located in the Suprachiasmatic nucleus (SCN), which is found in the hypothalamus (Harder and Oster, 2020). In most other animals, the circadian clock consists of a network of interconnected light-sensitive oscillatory units located in the retina, the pineal gland, and the brain (Tosini *et al.*, 2001; Falcón *et al.*, 2007). The biological clocks in avian species are also structured in this way. In birds, the endogenous rhythms result from the hypothalamus, in coordination with oscillators in the pineal gland and the retina (Gwinner & Brandstätter, 2001). The interactions between the circadian oscillators and the relative contribution of each internal oscillator are species-specific. This more complex and species-dependent structure of the avian circadian clock is suggested to provide the birds with adaptive properties to their habitat and way of living. Circadian oscillation in avian species is generated

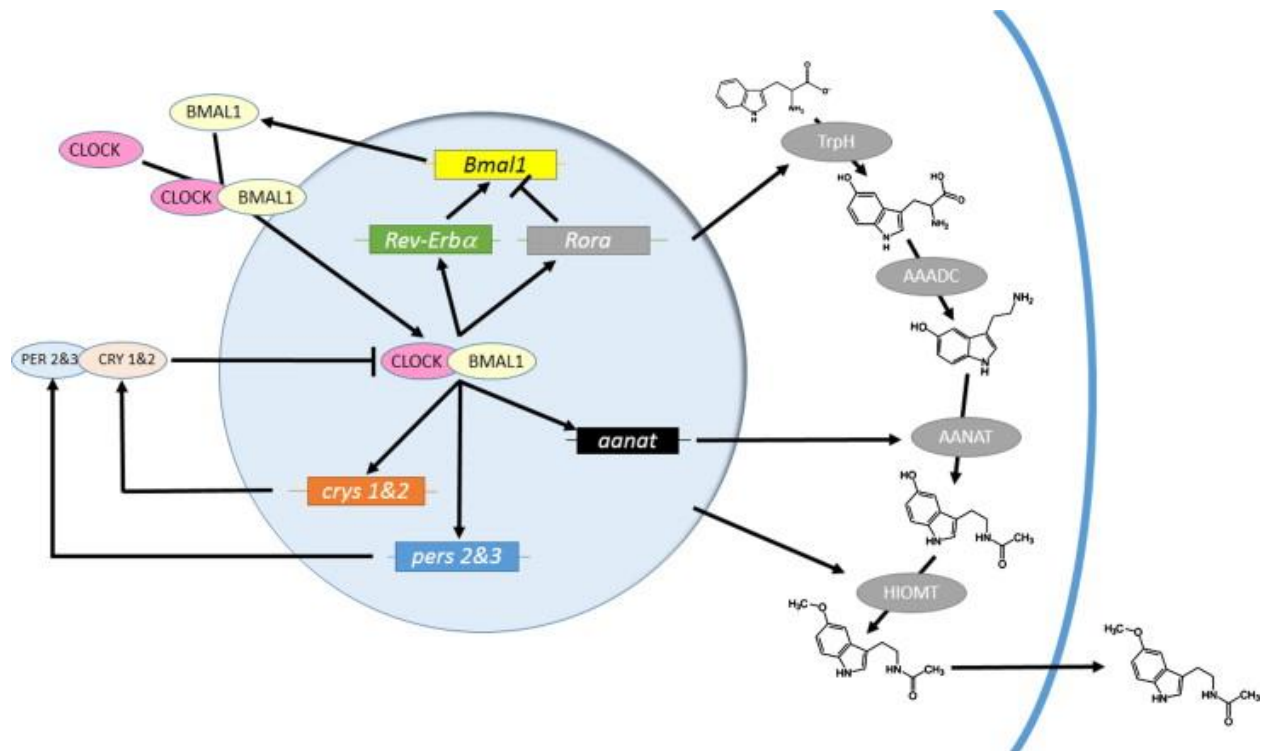


Fig. 1. "Schematic of the molecular clockworks regulating circadian patterns of melatonin biosynthesis in a retinal photoreceptor. Positive elements Clock and Bmal1 enter the nucleus and activate expression of genes whose promoters contain an E-Box. Among these are the negative elements period 2&3 (pers 2&3) and cryptochromes 1&2 (crys 1&2), Rev-Erba and Rora, which form a secondary loop regulating Bmal1 transcription, and output, clock-controlled genes such as arylalkylamine-N-actyltransferase (aanat). The pers and crys are translated, form heterodimers with other components, such as the casein kinases, and reenter the nucleus to interfere with Clock/Bmal1 activation. Melatonin biosynthesis pathways are indicated on the right. Amino acid tryptophan is converted to 5-hydroxytryptophan by tryptophan hydroxylase (TrpH). Aromatic amino acid decarboxylase (AAADC) then converts 5-hydroxytryptophan to 5-hydroxytryptamine (5HT; serotonin). Then, during the night, AANAT converts 5HT to N-acetylserotonin, a substrate for hydroxyindole-O-methyltransferase (HIOMT), which produces melatonin itself. Presumably, melatonin diffuses out of the cell at this time, although a release mechanism may exist." Figure taken from: Cassone, V. M. (2014). Avian circadian organization: a chorus of clocks. *Frontiers in neuroendocrinology*, 35(1), 76-88.

by a molecular feedback loop formed by a set of circadian clock genes (Jiang *et al.*, 2017; Cassone, 2014; Fig. 1). Some of the genes involved in this feedback loop are the three positive clock genes, *Clock*, *Bmal1*, and *Bmal2*, and four negative clock genes, *Cry1*, *Cry2*, *Per2*, and *Per3* (Cassone, 2014; Yang *et al.*, 2020). Melatonin plays an important role in the regulations of circadian and circannual rhythms, as a neurotransmitter between the different areas in the brain. Melatonin receptors are localized in many of the brain regions involved in cognitive and homeostatic processes. Thus, seasonal changes in melatonin secretion regulate key genes required for the neuroendocrine control of behaviour and physiology (Stevenson *et al.*, 2015). ALAN can impact this molecular clock mechanism. A study by Dominoni *et al.* (2013) found a clear correlation between ALAN and melatonin levels. In illuminated environments, birds showed significantly lower melatonin levels than birds kept in darkness. The lower melatonin levels coincided with increased locomotor activity. These findings match observations describing extension of diurnal activity in birds when exposed to artificial light. The onset and cessation of singing and foraging show the greatest divergence from the usual activity. Mockingbirds, *Mimus polyglottos*, feed their

nestlings in the late evening under ALAN (Stracey *et al.*, 2014). Another example is found in European blackbirds, which continue foraging longer into the evening and begin their mornings earlier when exposed to ALAN (Dutta, 2017).

Circannual rhythms

In addition to circadian rhythms, many organisms have developed circannual rhythms as well. The circannual clocks are also autonomous and are entrained by photoperiod and temperature (Lincoln, 2019). Birds use this circannual clock to time reproduction and migration. Migration is a very rhythmic occurrence. The timing of migration of birds is incredibly strict. Every year, it occurs at specific seasons and specific times of day. This very strict timing is heavily dependent on their internal biological clock. The onset of migration in both autumn and spring are determined by the circannual rhythm. Especially for birds wintering close to the equator, these endogenous rhythms are very present and of high biological importance. Near the equator, photoperiod is constant over the year and other potential *zeitgebers* such as temperature, precipitation and food abundance are too variable year over year to be used as external timing cues (Gwinner, 1996). This reliance on their internal biological rhythm became clear when studies were performed on captive birds. Many species of migratory birds, including sparrows, finches and warblers, exhibit two periods of *Zugunruhe* or 'migratory restlessness' in captivity at the same times of year that natural migration would occur. Even if the birds were kept in a constant light-dark cycle (LD 12:12), they expressed two periods of *Zugunruhe* approximately 6 months apart (Cassone, 2014).

Despite this strong internal clock, photoperiod and temperature are used to synchronize the rhythm to the environment. Not only are the endogenous rhythms rarely exactly 365 days long, but nature itself isn't constant either. Harsh winters or dry seasons may cause birds to deviate from their usual rhythms to compensate for the unusual environmental circumstances. When it comes to photoperiod, Gwinner (1989; 1996) theorized the following two major effects of daylight on circannual rhythms after performing captive experiments on the long-distance migrating garden warbler: (1) Short photoperiods advance the onset and end of post-juvenile moult and the onset of autumn migratory restlessness. (2) Long photoperiods advance the end of autumn migratory restlessness, the onset and end of the winter moult and the onset of spring migratory restlessness. The synchronization of autumn migration was theorized to be most important for young birds that have hatched from late clusters and would otherwise finish development and start migration too late in the year. The short photoperiods would cause the young birds to accelerate development and leave the breeding ground in time. The effects of longer photoperiods are thought to be twofold. The photoperiod would cause birds to end their autumn migration if they have flown too far south by their own biological clock. At the same time, it would enable these birds to initiate spring migration earlier. This is necessary to compensate for the extra distance they have traveled compared to other birds that may have spent the winter further north (Gwinner, 1996). An impaired perception of photoperiod due to ALAN may lead to migration that is desynchronized with the current environment. This synchrony between the internal biological clock and the environment is important for long-distance migratory birds, as they are often too far from their destination to receive external cues. Moreover, a study by Stevenson *et al.* (2015) found that birds with the greatest mismatch with the food

peak have the fewest surviving offspring. In addition, avian species living in temperate zones use the length of the day to predict the optimal timing of reproduction. An increase in day length indicates spring, which causes the birds to develop gonads (Dawson *et al.*, 2001). In winter, when photoperiod is short, gonadal activity and gonad size regress and become inactive (Cassone, 2014). Artificial lights simulate longer photoperiods, thus causing advanced onset in reproduction in some birds. Especially for birds living in an urban environment, the advanced onset of reproduction often leads to an extended breeding season. In a city population of European Blackbirds, the onset of reproduction had advanced as much as three weeks for both males and females even though the light intensity was relatively low (0.3 lx) (Partecke *et al.*, 2005). Moulting could also be advanced in these birds by up to 3 months under the influence of light (Helm *et al.*, 2013; Partecke *et al.*, 2005).

Phototaxis

Phototaxis is an animal's movements in response to light in the environment. Positive phototaxis (movement toward a light source) can most often be observed at night when, for example, moths and other insects are attracted to a porchlight or streetlamp. This phenomenon also applies to birds. ALAN causes disorientation and misorientation, causing the birds to fly into structures, often leading to their death, or waste energy by flying in circles. However, it is still unclear what mechanism causes migrating birds to be attracted towards artificial light. Several hypotheses have been proposed over the years. Poot *et al.* (2008) suggest it is likely that in some cases the intensity of the light effectively blinds the birds to a point where they can no longer see in the dark as well as they could when they were dark adapted. In that case, they can lose sight of the horizon or celestial cues, which makes them circle within a cone of light. The study measured birds' responses to different coloured lights, as well as different brightness. For white light, the responses to different amounts of light were indistinguishable. Under white and red light conditions, the birds were significantly disturbed and attracted to the light source. In green light, the birds were better oriented, significantly less disturbed, and significantly less attracted to the light source than in white and red light (Poot *et al.*, 2008; Fig. 2.). Another theory proposes the possibility that ALAN

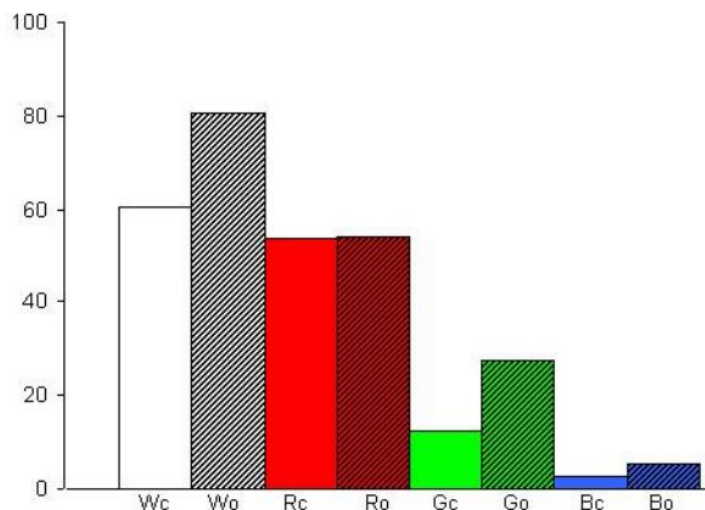


Fig. 2. "Percentage of bird (groups) responding to different light conditions: white (W), red (R), green (G), and blue (B) under clear (c) and overcast (o) conditions during the observation period." Figure taken from: Poot, H., Ens, B., De Vries, H., Donners, M., Wernand, M., & Marquenie, J. (2008). Green Light for Nocturnally Migrating Birds. *Ecology and Society*, 13(2).

interferes with a birds' magnetic compass (Gauthreaux & Belser, 2006). Birds use visual clues as well as a magnetic compass for orientation (Poot *et al.*, 2008). Though lights' effect on visual orientation is most obvious, magnetic orientation involves light as well. The mechanism of the magnetic compass is likely based on specific light receptors in the eye and is shown to not only be light dependent (Ritz *et al.*, 2000), but also wavelength dependent. The blue-green part of the light spectrum is used for magnetic compass orientation (Wiltschko & Wiltschko, 1995). Red light, however, disrupts magnetic orientation (Wiltschko *et al.*, 1993). The effects of disturbance and attraction are strongest on overcast nights, which suggests migratory birds use celestial cues for orientation. During cloudy or foggy weather, the birds cannot use celestial cues and may therefore be more dependent on the magnetic compass for orientation (Poot *et al.*, 2008).

To make matters worse, young birds may be more susceptible to the phototaxic effects of ALAN than adults. Two different experiments examining orientation of migratory birds found that adults were not affected by sky glow, but birds born that year were attracted to the light source (Gauthreaux, 1982). A possible explanation would be a lack of experience with the environment and environmental cues. The varying age-class attraction of birds to light also suggests that some older birds may learn not to approach artificial light sources (Montevecci, 2006). Either way, the increased vulnerability of offspring puts an enormous pressure on a species' fitness, as younger birds have the potential to produce more offspring than older generations in the remainder of their lifetime. A high proportion of young birds in a population is essential not only for the general survival of its species, but also to compensate for the increased mortality due to the recent changes in climate and environment.

Whatever the mechanism behind it may be, collisions with, for example, communication towers are a major source of mortality for birds, with several reports of single-night, single-tower casualty events of hundreds to thousands of individuals (Loss *et al.*, 2015). The birds' attraction to the lights on the towers during their nighttime migration often ends in collision with the structure or the supporting guy wires, especially during foggy and otherwise inclement weather when phototaxis is particularly strong. A study by Longcore *et al.* (2012) estimates that communication towers kill 6.6 million birds annually in the United States alone and roughly 220,000 birds in Canada. Total deaths by collision with man-made structures, not just communication towers, near 98 million to one billion birds each year across North America alone (Chepesiuk, 2009). Even if birds do not crash into objects, artificial light sources often cause them to change their flight path. Birds using a light on a tower as a horizon cue will often circle the tower (Herbert, 1970). In other cases, the unnecessary ascent and descent, long periods of circling, and other types of irregular behaviours take a lot more energy than the typical migratory flight that is often a straight path (Van Doren *et al.*, 2017). Aside from the excess energy expenditure, stray birds are also more susceptible to predation and changes to stopover ecology (Lebbin *et al.*, 2017). Birds that do not die from exhaustion may be delayed for days, as they have to compensate for the extra energy expense when regaining fat stores during migratory stopovers (Van Doren *et al.*, 2017). Lastly, deviation from the correct migration path may lead birds towards harmful city landscapes or other dangerous areas. A study by Stone (1906) tracked birds as they flew over a large lumberyard fire that attracted them during their nocturnal migration. The birds did not seem to change their flight direction, but they appeared to lower their flight altitude. Roughly 30 birds were burned to death as they flew too close to the flames. With this in mind, gas flares on offshore oil and gas platforms and at oil refineries likely also pose a significant threat to migrating birds at night (Gauthreaux and Belser, 2006).

In addition to the potentially lethal gas flares caused by oil platforms, another interesting effect has emerged from ALAN in marine ecosystems. The lights on these offshore oil platforms, like most artificial lights, also cause collision and exhaustion in marine birds, but there is a third danger hidden at these man-made metal islands. Offshore oil platforms rapidly develop into artificial reefs that create blooming marine communities (Montevecchi, 2006). These reefs attract and house flora, crustaceans, fishes, and squids (Carlisle *et al.*, 1964). The lighting attracts fishes and birds. Many nocturnal seabirds have a high prevalence of rods in their retina, more rhodopsin, and often larger eyes than related diurnal species (McNeil *et al.*, 1993). Thus, these species are likely more susceptible to artificial light. Many of the smaller planktivorous nocturnal species are highly sensitive to, and attracted to, ALAN. Especially species that feed on bioluminescent prey appear to have the greatest vulnerability to ALAN, which could be explained by a predisposition for light attraction. Many species of marine birds have been recorded feeding in ALAN. Wastewater dumped on site fertilizes the artificial reefs and provides feeding opportunities that attract scavenging gulls (Montevecchi, 2006). However, spilled oil and discharged oily drilling fluids contaminate the birds on site (Burke *et al.*, 2005). This concentration of birds at oil platforms also increases the chance of collision with the platforms itself, or nearby ships and vessels. In addition, the concentration of birds and fishes in a small area attracts avian predators, which causes an significantly increased risk of predation relative to the birds' usual habitat. Indirectly, it may also affect the habitats these birds would otherwise be foraging or nesting at.

Climate change

The ongoing climate crisis already poses a big threat to many species. Unfortunately, ALAN does not soften the negative consequences of climate change and may oftentimes even add to them. For example, increasing spring temperatures have altered vegetation phenology, often advancing the peak of food abundance. In turn, migration in certain birds has also been advancing, which leads to early nesting and hatching (Dutta, 2017). As described earlier, advances in the time of migration are not common in long-distance migratory birds due to their strong biological clock. Because the onset of migration is determined by endogenous rhythms, they have been unable to adapt to the changing climate. Species that do not migrate earlier have been steadily declining in population sizes. A study by Gil *et al.* (2014) suggested that the inability to advance their migration timing contributed to a rapid decline in European and North American long-distance migratory species. For example, though pied flycatchers (*Ficedula hypoleuca*) laid their eggs earlier in response to increasingly warmer spring temperatures, they did not advance reproduction enough to adapt to the advancement of the food peak. These birds spend their winters in West Africa, where they do not receive information about the environmental factors in Europe. Therefore, they have to rely on their circannual rhythm and current photoperiod instead. This significantly inhibits early migration, which would have allowed them to take advantage of extended breeding seasons. This mismatch with the changing climate has been associated with the decline of pied flycatcher populations (Helm *et al.*, 2013).

The effects of ALAN make it difficult for birds to distinguish between different photoperiods, hindering the synchronization and adaptability of the internal rhythms of migratory birds. This hindering of

synchronization would also hinder the advancement of migration onset due to climate change. The lack of advancement of migration causes a disparity between the timing of the food supply for young offspring and the reproductive behaviour in some birds. Additionally, a later arrival date due to disorientation from ALAN may significantly increase the extent of this desynchrony. The delay may cause the migratory birds to miss optimal conditions for nesting, foraging and other behaviours. The greater the mismatch between food availability and arrival date, the more likely a decline in population occurs (Stevenson *et al.*, 2015). A study by Cotton (2003) even goes so far as to suggest that the arrival of migratory birds at breeding and over-wintering grounds at the appropriate time is the primary determinant of success, survival, and fitness.

Another, mostly overlooked, issue regarding ALAN and climate change is the catastrophic decline in insect biomass. Some studies estimate a 76% to 98% decline in biomass over the last few decades (Goulson, 2019). This decline in insects is a result of several anthropogenic factors, including habitat loss and climate change, but some also note light pollution as a cause (Goulson, 2019; Owens *et al.*, 2020). Insects are a vital part in any ecosystem and their absence causes a wide range of problems. Birds also rely on insects, many being specialized insectivores. The drastic decline in insects has meant a drastic decrease in food abundance to avian species. This, in combination with the higher likelihood of missing the food peak due to direct effects of ALAN, may pose a significant threat to the survival of many bird species.

Reducing avian mortality

ALAN affects countless bird species in many locations, so one of our challenges is to find ways to reduce the attractiveness of lights to birds in the face of increasing human development, especially as artificial light spreads to conquer the globe. It is now up to ecologists to come up with and develop solutions for the ever-increasing photopollution.

The easiest solution to the detrimental effects of ALAN is to simply turn off the lights, especially when they do not explicitly serve a purpose. Though this solution is simple and practical, it is a significantly underused approach to reducing light pollution. Turning off unneeded exterior and interior lighting, reducing the brightness of lights that cannot be turned off and covering windows at night to prevent light leaking to outside could prove to be extremely useful. A study by Van Doren *et al.* (2017) showed that birds can recover almost immediately when lights are turned off. In their study, the removal of the light resulted in rapid changes in nocturnal migration behaviours, with birds dispersing, increasing flight speeds, and moving away from the site in a matter of minutes (Fig. 3). Peak fledging periods and most migration seasons are highly concentrated during a few weeks in the Northern and Southern hemispheres. Even just minimizing light pollution at these specific times could significantly reduce avian mortality. On offshore and land-based oil platforms, the flares have to periodically shut down for maintenance. This downtime could be scheduled to match the periods with the highest avian migration (Montevecchi, 2006).

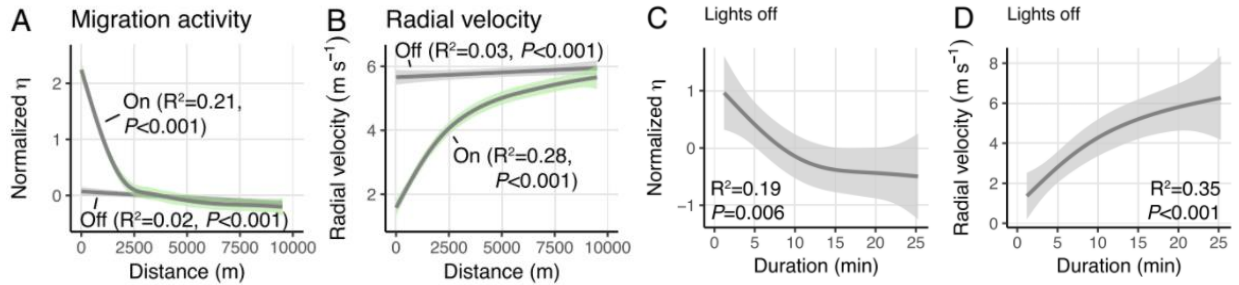


Fig. 3. “Spatial and temporal influence of the monument ‘Tribute in Light’ in New York on migratory birds. Migration activity (A and C) and radial velocity (B and D) at the installation pooled across years by distance from the study site (A and B) and activity as a function of time since the monument 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.” Figure taken from: Van Doren, B. M., Horton, K. G., Dokter, A. M., Klinck, H., Elbin, S. B., & Farnsworth, A. (2017). High-intensity urban light installation dramatically alters nocturnal bird migration. *Proc. of the Nat. Acad. of Sci.*, 114(42), 11175-11180.

In some places, like densely populated areas, turning off lights is not always possible or preferable. Most industrial installations require lights because of safety requirements or technical design (Poot *et al.*, 2008). Many offshore oil and gas installations are developed without the capability to switch off lights because it is considered unsafe due to explosion and corrosion risks on the platform. In cases like this where turning off lights is not an option, shielding lights and focusing the light on the areas where they are actually needed may also greatly reduce photopollution. For example, a lot of light from lamp posts is not directed directly at the ground, thus wasting a lot of light and energy while also causing significant ecological disturbances. By shielding the upwards projection of light, experiments by Reed *et al.* (1985) demonstrated reductions in attraction by endangered species at a coastal Hawaiian resort of 30-50%. Some cities such as Tucson, Arizona and Prague, Czech Republic already shield lights in their municipalities to reduce light pollution that interferes with astronomical observation (Montevecchi, 2006). In addition to the shielding of lampposts, floodlights on the ground that point upwards to illuminate buildings, bridges and monuments should be avoided. If the structures have to be illuminated, the floodlights should be placed on top, pointed downwards. Preferably, these guidelines are paired with the previous suggestion: During migration seasons, especially when weather conditions contribute to attraction and mortality, the floodlights should be turned off (Rich & Longcore, 2005). The shielding of lights would not only be useful in urban areas, but also in rural or isolated regions. For example, when it comes to marine environments, shielding of lights at oil platforms should both eliminate the upward focused light, to protect migrating species, and guard against increasing the incidence of light directed at the sea surface to avoid attracting and trapping fishes and invertebrates. This technique may also work on boats and vessels, as opposed to static structures. In 2000, California passed regulations requiring that squid fishing vessels shield their lights and use no more than 30,000 W per boat (Montevecchi, 2006). Observers are not required on these vessels, but many argue they should be. Currently, the system relies on self-reporting to regulate light pollution, but self-reporting does not always provide accurate or reliable information, especially of negative or illegal activity. Independent monitoring is widely accepted as a more valid and reliable means of assessment, especially when it comes to industries or individuals with vested interests in profits. These organizations benefit from limited self-regulation in the interest of profit margins. Observers are already

required on fishing vessels because of the potential harmful effects that fishing can have on marine ecology and the population numbers of fish. It would be relatively easy to have them check light levels every now and then. Montevecchi (2006) argues that a dedicated independent observer should also be mandatory when approving operations of offshore oil platforms. He argues that the threats from lights and flares at offshore platforms are at least as severe as the light pollution from fishing vessels and should thus require similar regulation.

An alternative to shielding would be to change the light colours to minimize the disorientation in birds for specific wavelengths. In some instances, this approach has already been adapted. Ceilometers, for example, are very bright spotlights to measure the height of the cloud ceiling. They are very useful to aviation, but it was discovered that their continuous bright lights periodically attracted and killed large numbers of birds that were migrating past them. Two important adaptations were introduced: (1) Ceilometers now illuminate the sky at intervals, rather than continuously. (2) They are filtered so that mainly ultraviolet light remains. Together, they nearly completely eliminated mortality among migratory birds due to ceilometers (Gauthreaux & Belser, 2006). The same is true for lighthouses. Lighthouses have saved many lives by keeping ships away from reefs, but their bright lights also occasionally attracted large numbers of birds. To combat this disruptive light, the lighthouses now rotate, often have a more focused beam, and generally have adapted their light to be composed of different wavelengths than they formerly did. Unfortunately, this approach would not work for industrial installations, as ultraviolet light is invisible to the human eye and the installations must be visible where people must be able to work safely during the night. Therefore, green light could be a great option, as this also significantly reduces disturbance and attraction in migrating birds (Poot *et al.*, 2008).

As mentioned previously, communication towers are also a big contributor to the mortality of migratory birds. Spread throughout the landscape, including both urban and rural areas, their universal presence causes great harm to the local bird populations. They carry mandatory safety lights to avoid collisions with airplanes. Research showed that replacing the continually burning lights with either red or white flashing lights can reduce mortality by 51-70% (Gehring *et al.*, 2009) and that towers with a height between 116 and 146 meter cause 16 times less mortality without supporting guy wires than comparably sized towers with guy wires (Gehring *et al.*, 2011). Additionally, taller towers kill exponentially more birds, likely as a combined result of their taller size, thus more area to cause collision, as well as their longer total guy wire length. Tall towers cause 5 times more mortality than medium towers, and 70 times more than medium unguyed towers (Gehring *et al.*, 2011) An analysis by Loncore *et al.* (2008) showed a strong positive correlation between tower height and bird mortality, even when controlling for the effect of lighting. The straight-forward solution would be to reduce the height of communication towers. Other possible approaches to reduce bird mortality include visually marking guy wires or placing new towers near existing ones rather than in undisturbed locations (Loss *et al.*, 2015).

Conclusion

All in all, we should aim to reduce artificial light at night as much as possible. Preferably turn off or remove lights wherever circumstances allow, and dimming, focusing or shielding the light in all other locations. Additionally, we should experiment with lights in different wavelengths and intervals for each application, trying to reduce avian mortality as much as possible. Many solutions are relatively easy to implement but would contribute substantially to the conservation of species. Therefore, I am of the opinion that more should be done to bring the issue of photopollution to the general public and the legislature. Though photopollution and its severe negative effects on nature has seen a stark increase in attention from the scientific community in the last few years, it has remained an issue that is relatively unknown to the general public. I sincerely hope to see this change in the near future so that some urgently-needed changes can be made. Step one is acknowledging there is a problem, step two is making the change.

References

- Bell-Pedersen, D., Cassone, V. M., Earnest, D. J., Golden, S. S., Paul, E., Hardin, P. E., *et al.* (2005). Circadian rhythms from multiple oscillators: lessons from diverse organisms. *Nat. Rev. Genet.*, 6, 544–556. doi: 0.1038/nrd1633
- Brüning, A., Hölker, F., Franke, S., Kleiner, W., & Kloas, W. (2016). Impact of different colours of artificial light at night on melatonin rhythm and gene expression of gonadotropins in European perch. *Sci. Total Environ.*, 543, 214–222. doi: 10.1016/j.scitotenv.2015.11.023
- Burke, C. M., Dovoren, G. K., & Montevecchi, W. (2003). Seasonal and spatial trends of marine birds along support vessel transects and at oil platforms on the Grand Banks. *Offshore oil and gas environmental effects monitoring: approaches and technologies*.
- Carlisle, J. G., Turner, C. H., & Ebert, E. E. (1964). Artificial habitat in the marine environment. Resources Agency of California, Department of Fish and Game.
- Cassone, V. M. (2014). Avian circadian organization: a chorus of clocks. *Frontiers in neuroendocrinology*, 35(1), 76-88.
- Chepesiuk, R. (2009). Missing the dark: health effects of light pollution.
- Cotton, P. A. (2003). Avian migration phenology and global climate change. *Proceedings of the National Academy of Sciences*, 100(21), 12219-12222.
- Dawson, A., King, V. M., Bentley, G. E., & Ball, G. F. (2001). Photoperiodic control of seasonality in birds. *J. Biol. Rhythms*, 16, 365-380. doi: 10.1177/074873001129002079
- Day, R. H., Rose, J. R., Prichard, A. K., & Streever, B. (2015). Effects of gas flaring on the behavior of night-migrating birds at an artificial oil-production Island, Arctic Alaska. *Arctic*, 68, 367–379.
- Dominoni, D. M., Goymann, W., Helm, B., & Partecke, J. (2013). Urban-like night illumination reduces melatonin release in European blackbirds (*Turdus merula*): implications of city life for biological time-keeping of songbirds. *Frontiers in zoology*, 10(1), 1-11.
- Dutta, H. (2017). Insights into the impacts of four current environmental problems on flying birds. *Energy, Ecology and Environment*, 2(5), 329-349.
- Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C. C. M., Elvidge, C. D., Baugh, K., *et al.* (2016). The new world atlas of artificial night sky brightness. *Sci. Adv.*, 2, e1600377. doi: 10.1126/sciadv.1600377

- Falcón, J., Besseau, L., Sauzet, S., & Boeuf, G. (2007). Melatonin effects on the hypothalamo-pituitary axis in fish. *Trends Endocrinol. Metab.*, 18, 81–88. doi: 10.1016/j.tem.2007.01.002
- Falcón, J., Torriglia, A., Attia, D., Viénot, F., Gronfier, C., Behar-Cohen, F., Martinsons, C., & Hicks, D. (2020). Exposure to Artificial Light at Night and the Consequences for Flora, Fauna, and Ecosystems. *Front. Neurosci.*, 14, 602796. doi: 10.3389/fnins.2020.602796
- Foster, J. G., Algera, D. A., Brownscombe, J. W., Zolderdo, A. J., & Cooke, S. J. (2016). Consequences of different types of littoral zone light pollution on the parental care behaviour of a freshwater teleost fish. *Water Air Soil Pollut.*, 227, 404. doi: 10.1007/s11270-016-3106-6
- Gaston, K. J., Bennie, J., Davies, T. W., & Hopkins, J. (2013). The ecological impacts of nighttime light pollution: a mechanistic appraisal. *Biol. Rev. Camb. Phil. Soc.*, 88, 912–927.
- Gaston, K. J., Visser, M. E., & Hölker, F. (2015). The biological impacts of artificial light at night: the research challenge. *Phil. Trans. R. Soc. B.*, 370, 20140133.
- Gauthreaux Jr, S. A., & Belser, C. G. (2006). Effects of artificial night lighting on migrating birds. *Ecological consequences of artificial night lighting*, 67-93.
- Gauthreaux, S. A. (1982). Age-dependent orientation in migratory birds. *Avian navigation*, 68-74.
- Gehring, J., Kerlinger, P., & Manville, A. M. (2009). Communication towers, lights, and birds: successful methods of reducing the frequency of avian collisions. *Ecological Applications*, 19(2), 505-514.
- Gehring, J., Kerlinger, P., & Manville, A. M. (2011). The role of tower height and guy wires on avian collisions with communication towers. *The Journal of Wildlife Management*, 75(4), 848-855.
- Gill, J. A., Alves, J. A., Sutherland, W. J., Appleton, G. F., Potts, P. M., & Gunnarsson, T. G. (2014). Why is timing of bird migration advancing when individuals are not?. *Proceedings of the Royal Society B: Biological Sciences*, 281(1774), 20132161.
- Goulson, D. (2019). The insect apocalypse, and why it matters. *Current Biology*, 29(19), R967-R971.
- Gwinner, E. (1989). Photoperiod as a modifying and limiting factor in the expression of avian circannual rhythms. *J. Biol. Rhythms*, 4, 237–250.
- Gwinner, E. (1996). Circadian and circannual programmes in avian migration. *Experimental Biology*, 199, 39-48.
- Gwinner, E., & Brandstätter, R. (2001). Complex bird clocks. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, 356, 1801-1810.
- Harder, L., & Oster, H. (2020). The tissue clock network: driver and gatekeeper of circadian physiology circadian rhythms are integrated outputs of central and peripheral tissue clocks interacting in a complex manner - from drivers to gatekeepers. *Bioessays*, 42, 1900158. doi: 10.1002/bies.201900158
- Helm, B., Ben-Shlomo, R., Sheriff, M. J., Hut, R. A., Foster, R., Barnes, B. M., & Dominoni, D. (2013). Annual rhythms that underlie phenology: biological time-keeping meets environmental change. *Proceedings of the Royal Society B: Biological Sciences*, 280(1765), 20130016.
- Herbert, A. D. (1970). Spatial disorientation in birds. *Wilson Bulletin*, 82, 400–419.
- Jiang, N., Wang, Z., Cao, J., Dong, Y., & Chen, Y. (2017). Effect of monochromatic light on circadian rhythmic expression of clock genes in the hypothalamus of chick. *Journal of Photochemistry and Photobiology B: Biology*, 173, 476-484.
- Kyba, C. C. M., *et al.* (2017). Artificially lit surface of Earth at night increasing in radiance and extent. *Sci. Adv.*, 3, e1701528.
- Lebbin, D. J., Harvey, M. G., Lenz, T. C., Andersen, M. J., & Ellis, J. M. (2007). Nocturnal migrants foraging at night by artificial light. *Wilson J Ornithol*, 119, 506–508.

- Lincoln, G. A. (2019). A brief history of circannual time. *J. Neuroendocrinol.*, 31, 1–12. doi: 10.1111/jne.12694
- Longcore, T., Rich, C., Mineau, P., MacDonald, B., Bert, D. G., *et al.* (2012). An estimate of mortality at communication towers in the United States and Canada. *PLoS One*, 7, e34025.
- Loss, S. R., Will, T., & Marra, P. (2015) Direct mortality of birds from anthropogenic causes. *Annu. Rev. Ecol. Evol. Syst.*, 46, 99–120.
- McLaren, J. D., Buler, J. J., Schreckengost, T., Smolinsky, J. A., Boone, M., Van Loon, E., *et al.* (2018). Artificial light at night confounds broad-scale habitat use by migrating birds. *Ecol. Lett.*, 21, 356–364. doi: 10.1111/ele.12902
- McNeil, R., Drapeau, P., & Pierotti, R. (1993). Nocturnality in colonial waterbirds: occurrence, special adaptations, and suspected benefits. *Current ornithology*, 187-246. Springer, Boston, MA.
- Montevecchi, W. A. (2006). Influences of artificial light on marine birds. *Ecological consequences of artificial night lighting*, 94-113.
- Owens, A. C., Cochard, P., Durrant, J., Farnworth, B., Perkin, E. K., & Seymoure, B. (2020). Light pollution is a driver of insect declines. *Biological Conservation*, 241, 108259.
- Partecke, J., Van't Hof, T. J., & Gwinner, E. (2005). Underlying physiological control of reproduction in urban and forest-dwelling European blackbirds *Turdus merula*. *J. Avian Biol.*, 36, 295-305. doi: 10.1111/j.0908-8857.2005.03344.x
- Poot, H., Ens, B., De Vries, H., Donners, M., Wernand, M., & Marquenie, J. (2008). Green Light for Nocturnally Migrating Birds. *Ecology and Society*, 13(2).
- Ramos, B. C. R., Moraes, M., Poletini, M. O., Lima, L. H. R. G., & Castrucci, A. M. L. (2014). From blue light to clock genes in zebrafish ZEM-2S cells. *PLoS One*, 9, e106252. doi: 10.1371/journal.pone.0106252
- Rich, C., & Longcore, T. (2006). Effects of artificial night lighting on migrating birds. *Ecological consequences of artificial night lighting*.
- Riley, W. D., Davison, P. I., Maxwell, D. L., & Bendall, B. (2013). Street lighting delays and disrupts the dispersal of Atlantic salmon (*Salmo salar*) fry. *Biol. Conserv.*, 158, 140–146. doi: 10.1016/j.biocon.2012.09.022
- Ritz, T., Adem, S., & Schulten, K. (2000). A model for photoreceptor-based magnetoreception in birds. *Biophysical Journal*, 78, 707–718.
- Roth, L. S., & Kelber, A. (2004). Nocturnal colour vision in geckos. *Proc. of the Royal Soc. of London. B. Bio. Sci.*, 271(suppl_6), S485-S487.
- Saini, R., Jaskolski, M., & Davis, S. J. (2019). Circadian oscillator proteins across the kingdoms of life: structural aspects. *BMC Biol.*, 17, 13. doi: 10.1186/s12915-018-0623-3
- Somanathan, H., Borges, R. M., Warrant, E. J., & Kelber, A. (2008). Nocturnal bees learn landmark colours in starlight. *Current Biology*, 18(21), R996-R997.
- Stevenson, T. J., Visser, M. E., Arnold, W., Barrett, P., Biello, S., Dawson, A., ... & Helm, B. (2015). Disrupted seasonal biology impacts health, food security and ecosystems. *Proceedings of the Royal Society B: Biological Sciences*, 282(1817), 20151453.
- Stone, W. (1906). Some light on night migration. *Auk.*, 23, 249–252.
- Tracey, C. M., Wynn, B., & Robinson, S. K. (2014). Light pollution allows the northern mockingbird (*Mimus polyglottos*) to feed nestlings after dark. *The Wilson Journal of Ornithology*, 126(2), 366-369.
- Sullivan, B. G., Wilson, A. D. M., Gutowsky, L. F. G., Patrick, P. H., Sills, M., & Cooke, S. J. (2016). The behavioral responses of a warmwater teleost to different spectra of light-emitting diodes. *N. Am. J. Fish. Manag.*, 36, 1000–1005. doi: 10.1080/02755947.2016.1141123d

- Titulaer, M., Spoelstra, K., Lange, C. Y., & Visser, M. E. (2012). Activity patterns during food provisioning are affected by artificial light in free living great tits (*Parus major*). *PLoS One*, 7(5), e37377.
- Tosini, G., Bertolucci, C., & Foa, A. (2001). The circadian system of reptiles: a multioscillatory and multiphotoreceptive system. *Physiol. Behav.*, 72, 461–471. doi: 10.1016/S0031-9384(00)00423-6
- Van Doren, B. M., Horton, K. G., Dokter, A. M., Klinck, H., Elbin, S. B., & Farnsworth, A. (2017). High-intensity urban light installation dramatically alters nocturnal bird migration. *Proc. of the Nat. Acad. of Sci.*, 114(42), 11175-11180.
- Van Langevelde, F., Ettema, J. A., Donners, M., WallisDeVries, M. F., & Groenendijk, D. (2011). Effect of spectral composition of artificial light on the attraction of moths. *Bio. conservation*, 144(9), 2274-2281.
- Verheijen, F. J. (1981). Bird kills at tall lighted structures in the USA in the period 1935–1973 and kills at a Dutch lighthouse in the period 1924–1928 show similar lunar periodicity. *Ardea*, 69, 199–203.
- Wiltschko, W., & R. Wiltschko. (1995). Migratory orientation of European robins is affected by the wavelength of light as well as by a magnetic pulse. *Journal of Comp. Phys.*, A 177, 363–369.
- Wiltschko, W., U. Munro, H. Ford, & R. Wiltschko. (1993). Red light disrupts magnetic orientation of migratory birds. *Nature*, 364, 525–527.
- Yang, Y., Liu, Q., Wang, T., & Pan, J. (2020). Wavelength-specific artificial light disrupts molecular clock in avian species: A power calibrated statistical approach. *Environ. Pollut.*, 265(pt B), 114206. doi: 10.1016/j.envpol.2020.114206