

Research

Green Light for Nocturnally Migrating Birds

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ABSTRACT. The nighttime sky is increasingly illuminated by artificial light sources. Although this ecological light pollution is damaging ecosystems throughout the world, the topic has received relatively little attention. Many nocturnally migrating birds die or lose a large amount of their energy reserves during migration as a result of encountering artificial light sources. This happens, for instance, in the North Sea, where large numbers of nocturnally migrating birds are attracted to the many offshore platforms. Our aim is to develop bird-friendly artificial lighting that meets human demands for safety but does not attract and disorient birds. Our current working hypothesis is that artificial light interferes with the magnetic compass of the birds, one of several orientation mechanisms and especially important during overcast nights. Laboratory experiments have shown the magnetic compass to be wavelength dependent: migratory birds require light from the blue-green part of the spectrum for magnetic compass orientation, whereas red light (visible long-wavelength) disrupts magnetic orientation. We designed a field study to test if and how changing light color influenced migrating birds under field conditions. We found that nocturnally migrating birds were disoriented and attracted by red and white light (containing visible long-wavelength radiation), whereas they were clearly less disoriented by blue and green light (containing less or no visible long-wavelength radiation). This was especially the case on overcast nights. Our results clearly open perspective for the development of bird-friendly artificial lighting by manipulating wavelength characteristics. Preliminary results with an experimentally developed bird-friendly light source on an offshore platform are promising. What needs to be investigated is the impact of bird-friendly light on other organisms than birds.

Key Words: *artificial light; bird-friendly lighting; ecological light pollution; light color; magnetic compass; nocturnally migrating birds; orientation*

INTRODUCTION

For millions of years, plants and animals evolved under a day–night cycle, where the bright light of the sun during the day was replaced at night by weak light from the stars and sunlight reflected off the moon and planets. This situation ended very recently when humans started to artificially light the nighttime sky, which is especially clear in wealthy industrialized areas (Cinzano et al. 2001). Because animals (including man) and plants did not evolve under these artificial conditions, nighttime lighting may have serious negative consequences for the ecosystem, which made Longcore and Rich (2004) coin the term “ecological light pollution,” after Verheijen (1985) had coined the term “photopollution”

in 1985. According to Rich and Longcore (2006), the vast majority of conservation studies have focused on the daytime. As a result, we are just starting to appreciate the magnitude of the ecological consequences of artificial night lighting.

Artificial night lighting affects the natural behavior of many animal species. It can disturb development, activity patterns, and hormone-regulated processes, such as the internal clock mechanism; see references in Rich and Longcore (2006). Probably the best-known effect, however, is that many species are attracted to, and disoriented by, sources of artificial light, a phenomenon called positive phototaxis. Apart from insects, birds that migrate during the night are especially affected (Verheijen 1958). This

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may cause direct mortality, or may have indirect negative effects through the depletion of their energy reserves. Reviewing the literature, Gauthreaux and Belser (2006) conclude that “all evidence indicates that the increasing use of artificial light at night is having an adverse effect on populations of birds, particularly those that typically migrate at night.”

The reason why migrating birds are attracted toward artificially lit structures remains obscure. Gauthreaux and Belser (2006) discuss several hypotheses, including the possibility that artificial lighting interferes with the magnetic compass. It is assumed that migrating birds use visual cues (Emlen 1967, Evans Ogden 1996, Åkesson and Bäckman 1999, Mouritsen and Larsen 2001) as well as a magnetic compass mechanism (Wiltschko and Merkel 1966, Emlen et al. 1976, Wiltschko and Wiltschko 1995a, Deutschlander et al. 1999, Wiltschko and Wiltschko 2003) for orientation. It is clear that light is an important factor in using visual cues, but the second mechanism involves light as well. Magnetic orientation is probably based on specific light receptors in the eye and shown not only to be light dependent (Ritz et al. 2000), but also wavelength dependent: migratory birds require light from the blue-green part of the spectrum for magnetic compass orientation (Wiltschko and Wiltschko 1995b, 2001, Muheim et al. 2002) whereas red light, the long-wavelength component of light, disrupts magnetic orientation at least in laboratory conditions (Wiltschko et al. 1993). During overcast nights, the birds cannot use celestial cues and may be more dependent on the magnetic compass for orientation. In line with the hypothesis that artificial night lighting interferes with the magnetic compass, it is well established that during overcast nights, birds are more affected by artificial lights than on clear nights (Cochran and Graber 1958, Herbert 1970, Avery et al. 1977, Evans Ogden 1996, Wiese et al. 2001, Evans Ogden 2002). Resident birds are less affected, or even unaffected as they get accustomed to the presence of artificial light, do not use magnetic compass orientation, or lack this mechanism altogether (Mouritsen et al. 2005).

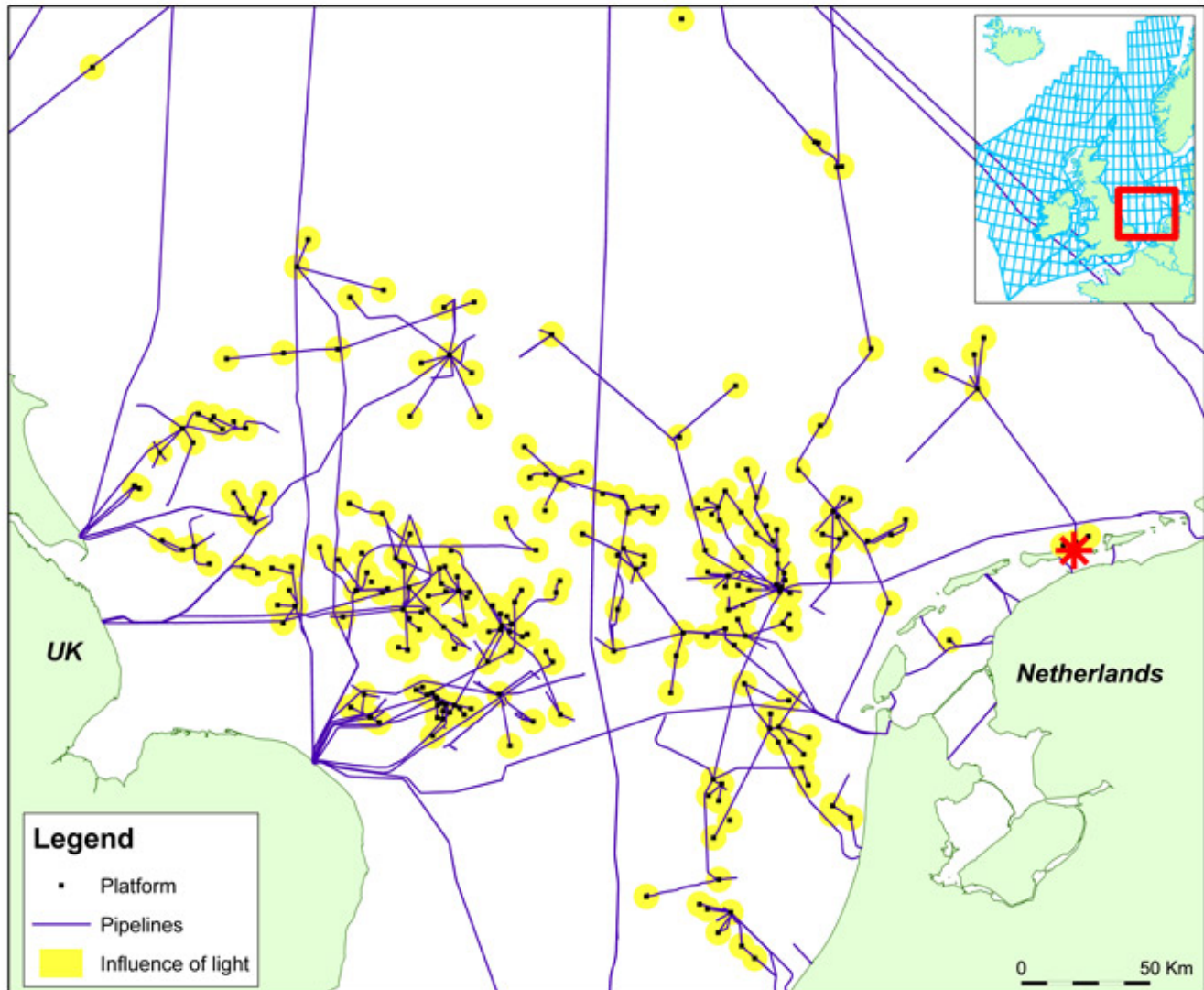
Irrespective of the precise mechanism, it is clear that artificial lights may interfere with the birds' ability to orient themselves (Evans Ogden 1996). Nocturnal bird kills occur wherever a lit obstacle, such as a tall building, lighthouse, or offshore installation, extends into an air space where birds are flying

(Verheijen 1958, 1985, Evans Ogden 1996, Wiese et al. 2001, Evans Ogden 2002). Globally, hundreds of millions of migrating birds are affected by the presence of artificial light on a yearly basis, many of which do not survive the encounter. The potential consequences can be excessive for sea areas with a high density of offshore installations. For the southern North Sea, for instance, it is impossible for a bird to cross without encountering two to ten installations (Fig. 1). Millions of seabirds, waterbirds, raptors, owls, shorebirds, gulls, terns, and songbirds pass through this area on their migrations back and forth between their breeding areas and wintering areas (Fig. 2). What can be done to minimize the losses among these migrants caused by the many offshore installations?

In an unpublished study, Marquenie and van de Laar (2004) investigated the behavior of migrating birds around offshore installations in the southern North Sea in the period 1992–2002. They observed that the milling behavior of dense—often mixed species—flocks only occurs during overcast nights (>80% cloud cover) and is most concentrated between midnight and dawn. In order to prove the cause-effect relation of lighting of offshore installations, they performed several experiments during two nights in November 2000 in which they manipulated the lighting of a gas-production platform (gas-production platform L5, situated 70 km offshore of the Dutch coast). When the lights were switched on, the number of birds on and around the platform quickly increased and when the lights were switched off, the birds rapidly dispersed from the platform, showing that it was indeed the artificial lighting that attracted the birds. A typical example is given in Table 1. In a second experiment on the same platform, they assessed the impact of partial lighting. It was shown that the influence of lighting increases with power (i.e., light intensity) and skyward-directed position (Table 2). It was estimated that the influence of full lighting (30 kW) extends to 3–5 km.

The easiest solution to this problem, turning off the lights (Evans Ogden 1996, Marquenie and van de Laar 2004), is not feasible for most offshore installations because of safety requirements or technical design. Many offshore installations in the North Sea and elsewhere are developed without the capability to switch off lights because this is regarded as undesirable because of explosion and corrosion risks. Retrofitting offshore installations also proved to be extremely expensive. Apart from

Fig. 1. Map of the southern section of the North Sea with existing production platforms in 2007. For each production platform, the potential impact zone of 5 km is indicated in yellow. The inset indicates where this area is located in the southern part of the North Sea. The red star indicates our study area.



redrawing the platform electrical scheme, it requires explosion-proof switches, installing switch wires, and temporarily taking the platform out of production.

A promising alternative would be to change light color, as laboratory studies show that birds are only disoriented under specific wavelength conditions (Wiltshcko and Wiltshcko 1995b, 1999, 2001,

Muheim et al. 2002). This idea dates back to A. L. Thomson, who suggested in 1926 that changing light color could result in a decline of the number of birds affected by artificial light (Thomson 1926). When the longer wavelengths of ceilometers (very bright vertically pointed spotlights that were developed in the late 1940s to measure the height of the cloud ceiling) were filtered so that mainly ultraviolet light remained, massive mortalities

Fig. 2. Schematized maps of the migrations of various bird groups through and around the North Sea area (van de Laar 1999). The following groups are distinguished: seabirds and waterbirds (black lines), raptors (green lines), shorebirds (blue lines), gulls and terns (orange lines), and songbirds (red lines). From top left to bottom right, maps are for July, August, September, October, November, and December.

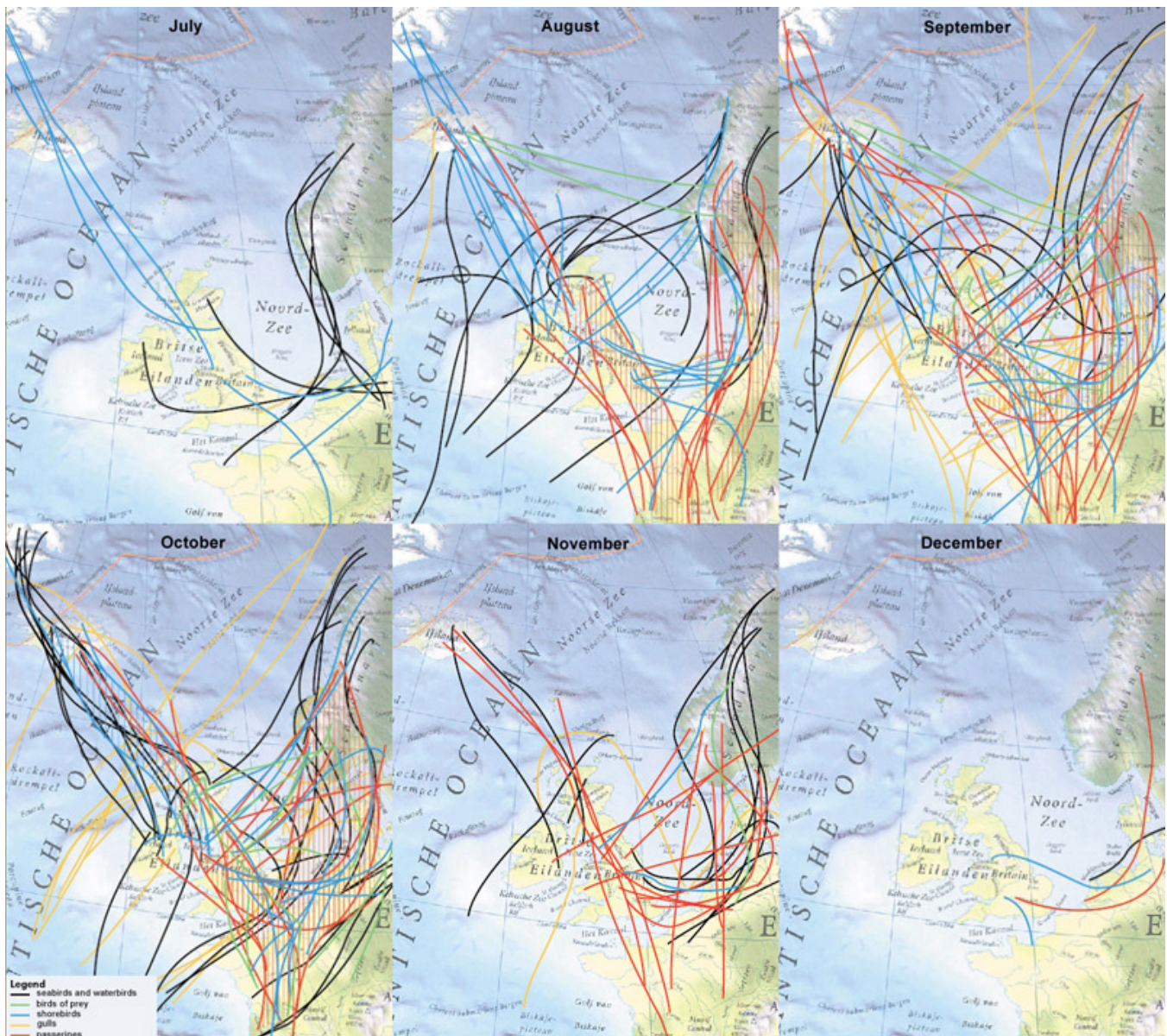


Table 1. Typical reaction rate of birds to light at sea during cloudy night migration as measured on the gas-production platform L5 (Marquenie and van de Laar 2004). The intensity of the lights when all lights were on, including main deck lights, was 30 kW.

| Time in minutes after lights on | Number of birds |
|---------------------------------|-----------------|
| 7 | 200–250 |
| 12 | 1000 |
| 20 | 1500 |
| 25 | 2000 |
| 30 | 4000–5000 |

| Time in minutes after lights off | Number of birds |
|----------------------------------|----------------------|
| 3 | Significant decrease |
| 15 | All gone |

among migratory birds due to these ceilometers were essentially eliminated (Gauthreaux and Belser 2006). However, being invisible to the human eye, ultraviolet light is not an option for offshore installations that must be visible to humans at a distance and where people must be able to work safely during the night. Thus, the challenge consists of developing bird-friendly lighting that is visible to the human eye, but does not attract and disorient nocturnally migrating birds. As a first step, we tested the response of nocturnally migrating birds to artificial lights of different colors during autumn migration in a field situation far removed from other artificial light sources.

METHODS

Our experiment was carried out directly next to a production site of the Nederlandse Aardolie Maatschappij (NAM) for natural gas on the eastern part of the Dutch Frisian (or Barrier) isle Ameland (53°45' N 5°68' E) (Fig. 3). This production site is located behind the North Sea beach, surrounded by sand dunes, and at about 10 km distance from the nearest village with artificial night lighting. During nighttime, the site is not artificially lit.

A 4.8-m lamp post with two identical 1000 W metal-halide lamps was used, directed northeastward at a 110° angle toward the sky. Lamps were alternately covered with red, green, blue or three opaque white Perspex filters. The opaque filters were used to control for intensity effects of the light. Absolute values of intensity and spectral composition measured at 0.57 m from the lamp and filter are shown in Fig. 4. Initially, measurements with white light did not include the Perspex filters. Thus, the measurements with white light were of variable light intensity. Measurements indicated that for wavelengths exceeding 450 nm, the three opaque white Perspex filters reduced illumination to 40% of the initial value.

Bird responses to the different colors were observed by the first author with the naked eye from an observation cabin made of wood and clear Perspex at some distance (about 15 m) behind the lamp standard in the shadow of the lights. In this arrangement, the observer was invisible to approaching birds, preventing a fright response from the birds. Observations started around 22:00 in the evening, as this turned out to be the time that migrants started to arrive on the island, and lasted throughout the night, except on nights with no or very little migration. Throughout the night,

Table 2. Relationship between light intensity and the number of birds attracted to gas-production platform L5 (Marquenie and van de Laar 2004). Disconnecting different light groups varied light intensity: beacon and obstruction lights (300 W), light in crane (1500 W), helicopter platform (160 W), and landing lights (480 W). When all lights were on, total intensity was 30 kW.

| Installed light sources | Type of lighting | Number of birds |
|-------------------------|--|---|
| 300 W | Red and green safety lights | None |
| 1500 W | Sodium floodlights of crane | Small number |
| 1960 W | Above sources plus helideck perimeter lighting | Limited numbers |
| 640 W | Upward helideck TL lights | Numbers clearly increase |
| 30000 W | Mostly TL (400x36 W) and sodium floodlights (20x400 W) | Large to very large numbers in times of heavy migration |

observation periods were about 45 min per light color, alternated with 15-min breaks. In all, observations were collected over the course of 41 nights during autumn migration in 2003 (September–November) under various weather conditions. Moon phases were noted according to the monthly sun- and moon-phase calendar for Amsterdam. Cloud coverage was estimated on a scale of one-eighth of the sky covered as visible from the observation site. Wind direction, wind force, and precipitation were also noted, but not used in the subsequent analysis. Two categories of bird responses were distinguished: oriented flight (no reaction) and attraction to the light source (reaction). To avoid pseudoreplication due to group effects, both individual birds and bird groups were treated as single observations. As it was hard to identify birds at a species level, all observations were treated the same. The observed species were mostly passerines (thrushes and smaller songbirds), but also included some shorebirds, ducks, and geese.

Oriented flight was defined as flying in a straight line in the seasonally appropriate direction. As we mainly observed migrating birds coming from Scandinavia, we assumed a general North–South movement as being seasonally appropriate; see also Fig. 2. Birds flying straight lines but in different directions were not taken into account because they were most likely not autumn migrants. Directions were estimated when the bird or bird group flew

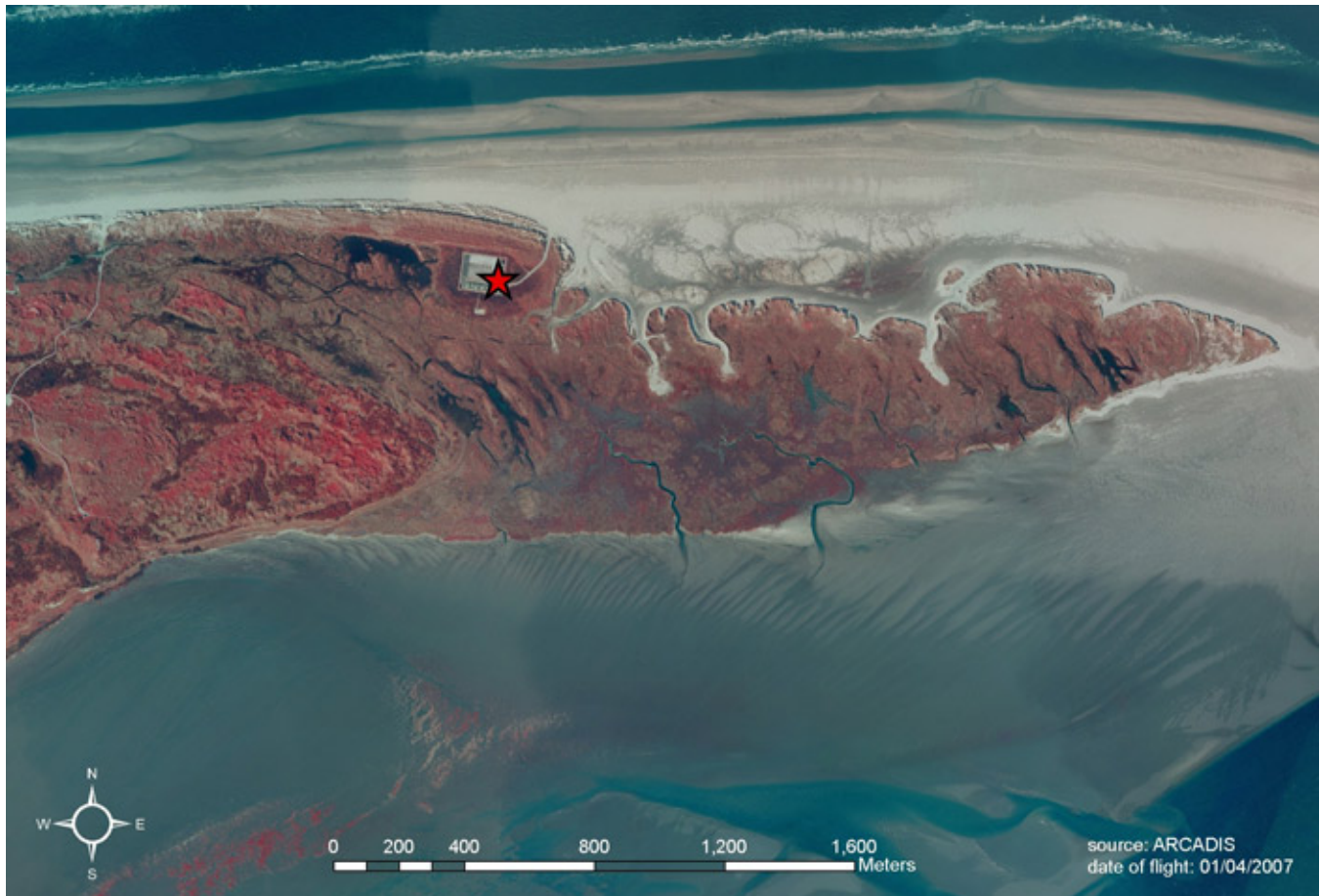
over the light source, which made it visible to the observer. Flight altitude of birds varied with weather conditions and species between ca. 10–100 m above the light source: birds flying higher could not be seen and were thus not included in this study.

We employed hierarchical log-linear modeling to statistically separate the possible effect of light conditions (white, red, green, and blue), overcast conditions (cloudy with more than 50% cloud cover or clear with at most 50% cloud cover), and moonlight (less than or equal to half moon, or more than half moon) on the reaction of the birds (reaction or no reaction).

We subsequently employed logistic regression to test the direction of the relationship between peak wavelength of the light and reaction of the birds. This analysis was necessarily restricted to the observations with red, green, and blue light and we included cloud cover as an additional independent variable.

Statistical analyses were performed using SPSS 15.0 for Windows (Release 15.0.1 dated 22 Nov 2006).

Fig. 3. Aerial view of the study area on 1 April 2007 (false color image produced by ARCADIS). The uninhabited eastern cape of the barrier island Ameland (Dutch Wadden Sea) is shown. The red star indicates the location of the artificial light source used for experiments.



RESULTS

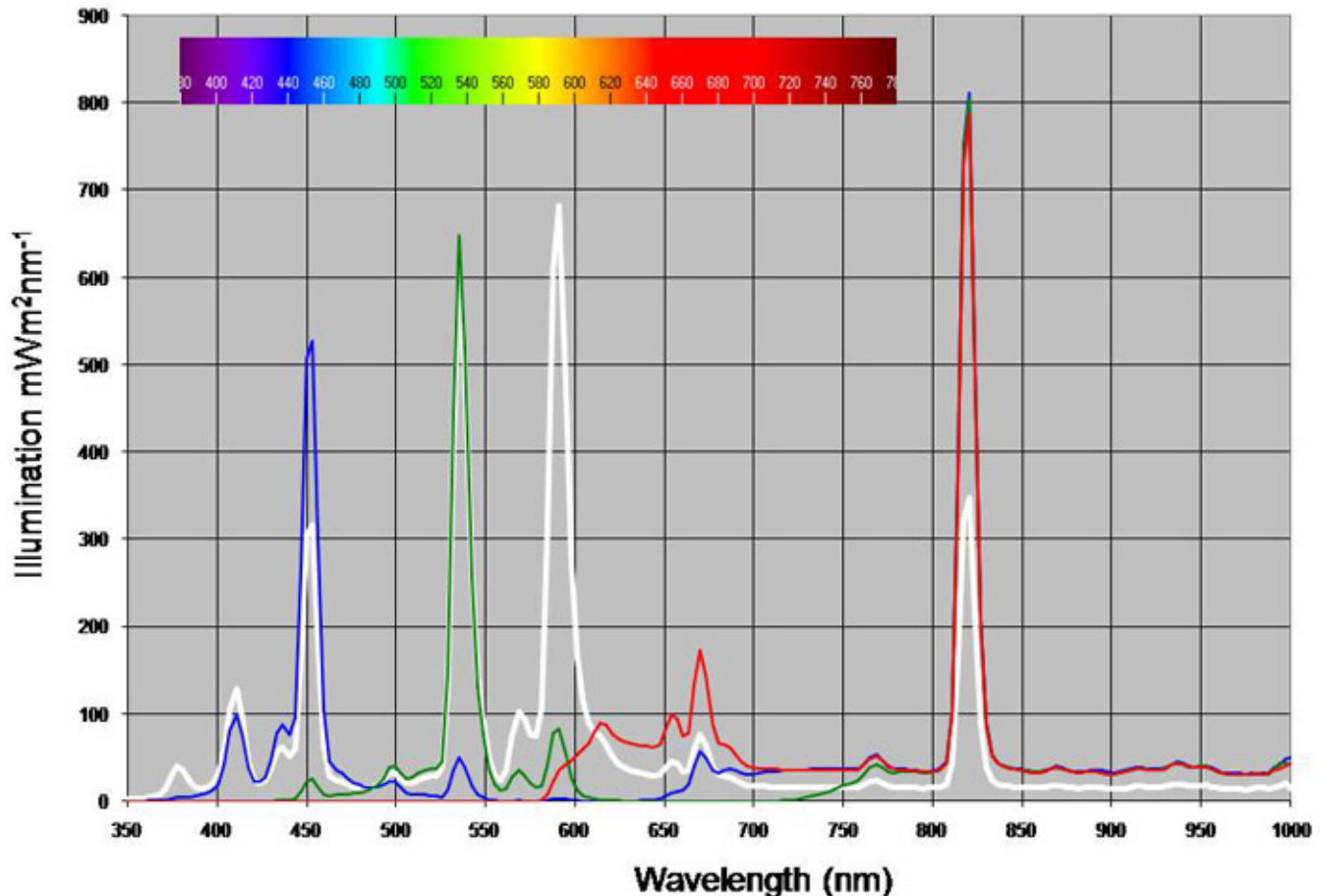
We obtained bird observations for all lamp types and weather conditions on different nights during the observation period. Light configurations (two types were used each night) were changed regularly in order to prevent possible order effects. The bird responses in all situations, including sample sizes, are given in Table 3.

Bird responses to the three different white-light conditions were statistically indistinguishable (Pearson $\chi^2 = 4.945$, $df = 2$, $P = 0.084$) and thus all white-light data, irrespective of intensity, were totalled for further analysis. Under white-light

conditions, the birds were significantly disturbed and attracted to the light source. The same is true for the red-light condition. In blue-light conditions, birds generally followed a seasonally appropriate migratory direction. In green light, birds were less well oriented than in blue light, but significantly less disturbed or attracted than in red and white light (Fig. 5). The effects of disturbance and attraction were strongest on overcast nights, regardless of lamp configuration, indicating primary use of celestial cues for migratory orientation.

We started the log-linear analysis with the fully saturated model including reaction (REACT), light conditions (COLOR), overcast conditions (CLOUD),

Fig. 4. The spectral shape of, respectively, the diffuser filter (white line), the blue filter (blue line), the green filter (green line), and the red filter (red line).



and moonlight conditions (MOON), i.e., the generating class of this model is REACT*COLOR* CLOUD*MOON. Table 4 shows the significance of all two-way and three-way interactions in this model involving the variable REACT, i.e., a reaction by the birds. There were highly significant two-way interactions between COLOR and REACT, and between CLOUD and REACT. The three-way interaction MOON*CLOUD*REACT bordered significance. We obtained the best-fitting hierarchical log-linear model ($\chi^2 = 9.867$, $df = 11$, $P = 0.542$) using backward elimination of terms, i. e., non-significant terms ($P > 0.05$) were dropped, starting with the least significant term. Comparing the best-fitting model with the model that excluded

the interaction between COLOR and REACT indicated that birds responded differently to different light conditions (partial $\chi^2 = 153.68$, $df = 3$, $P < 0.0001$). Comparing the best-fitting model with the model that excluded the interaction between CLOUD and REACT indicated that birds were also affected by overcast conditions (partial $\chi^2 = 13.71$, $df = 1$, $P < 0.001$). We found no effect of moonlight.

Logistic regression indicated that the probability that birds reacted to the light significantly increased with wave length of the light ($B = 0.013$, $Wald = 28.0$, $df = 1$, $P < 0.001$) and cloud cover ($B = 0.014$, $Wald = 4.8$, $df = 1$, $P = 0.029$). Thus, birds were

Table 3. Reaction of nocturnally migrating birds to different light conditions (peak wavelength indicated) under clear and overcast skies. It was noted that the red part of the spectrum is best characterized by a shoulder between 590–680 nm. The number of observations is given in parentheses, where groups are counted as a single observation.

| Condition | Peak wavelength (nm) | % bird reaction clear sky | % bird reaction overcast conditions |
|------------------|----------------------|---------------------------|-------------------------------------|
| White (diffuser) | — | 60.5 (n = 38) | 80.8 (n = 156) |
| Red | 670 | 53.8 (n = 13) | 54.2 (n = 24) |
| Green | 535 | 12.5 (n = 8) | 27.3 (n = 77) |
| Blue | 455 | 2.7 (n = 37) | 5.3 (n = 38) |

more likely to respond to the light when it had a long wave length, i.e., when it was red, and when cloud cover was high, i.e., on overcast nights.

DISCUSSION AND CONCLUSION

As in other field studies, strongest bird responses were found in white light, which seems to interfere with visual orientation on celestial cues (Verheijen 1958, Evans Ogden 1996): the artificial light becomes a strong false orientation cue and birds can get trapped by the beam (Verheijen 1958, 1985).

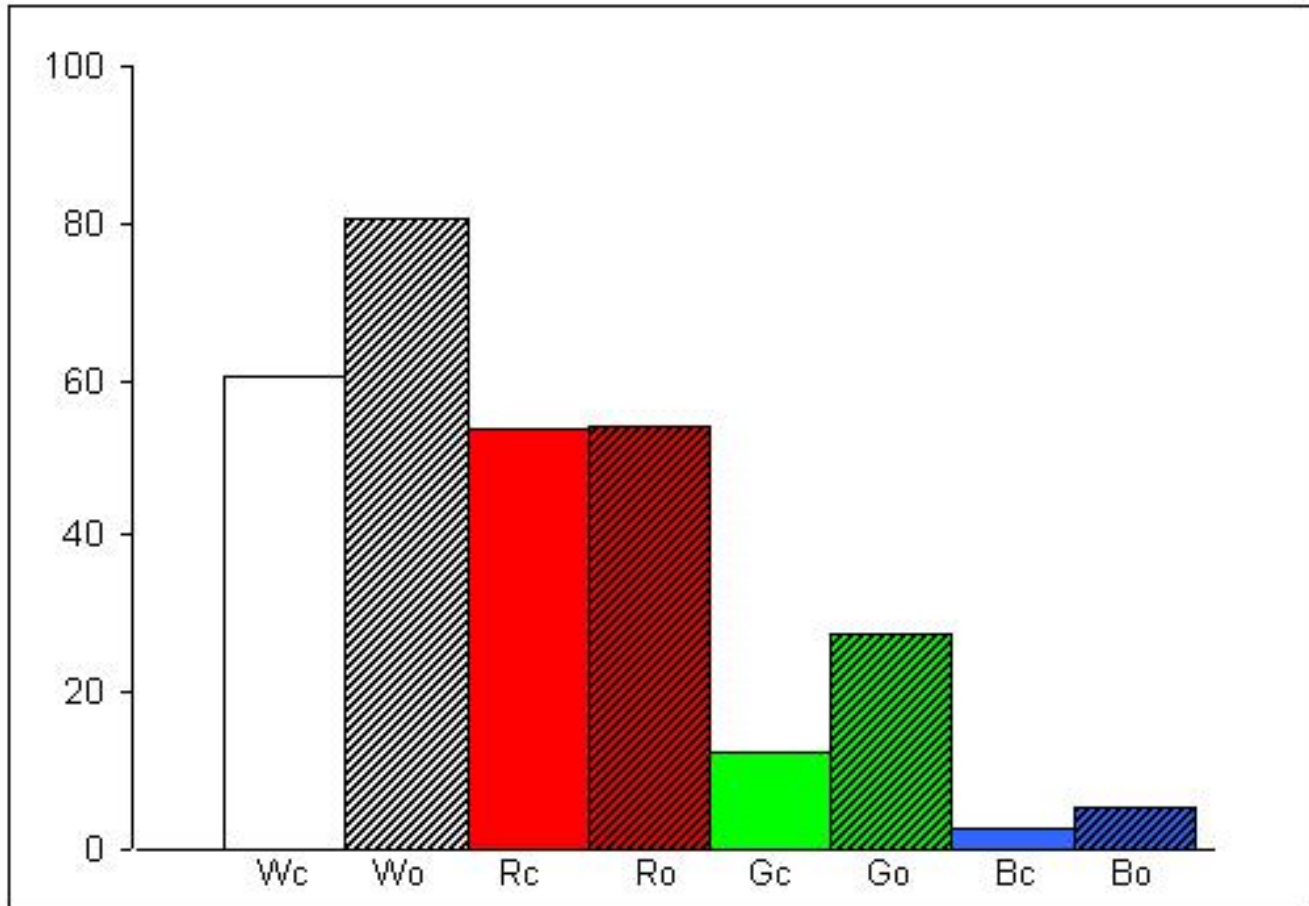
The bird responses observed in the colored-light conditions are similar to those of previous studies in the laboratory where red light caused disorientation by impairing magnetoreception (Wiltschko et al. 1993, Wiltschko and Wiltschko 1995b). In our study, birds were oriented in the seasonally appropriate migratory direction in blue light (Wiltschko et al. 1993, Wiltschko and Wiltschko 2001). As in these earlier laboratory studies, it was found that green light caused no or minor disturbance of orientation (Wiltschko and Wiltschko 1995b, Wiltschko et al. 2000, 2001, Wiltschko and Wiltschko 2001).

It is unlikely that differences in responses to various light conditions in our study were caused by differences in intensity. Red light caused disorientation at low light intensity, whereas the relatively high-intensity green light caused less

disorientation, even though birds are optimally sensitive to the green part of the spectrum (Maier 1992). Our results show also that bird responses to all light conditions are strongest on overcast nights when moon and starlight are unavailable as orientation cues. This finding is consistent with the outcome of previous research (Verheijen 1958, Evans Ogden 1996, Marquenie and van de Laar 2004). Overall, the results of our field study fit the hypothesis based on laboratory work that white and red light interfere with the magnetic compass of migrating birds. This magnetic compass is especially important to birds during overcast nights, when celestial cues are not visible. We did not find an effect of moonlight, but this could be due to small sample sizes. With larger sample sizes, we could have distinguished more than the two moonlight classes used in this study.

The impression that we derived from our observations on oil platforms leading up to this study was that birds could be attracted from up to 5 km distance with full lighting (30 kW). With the methodology of this study, we could not see birds flying much higher than 100 m, but the two lamps that we used were only 1 kW each. However, we cannot rule out the possibility that the birds that passed by in this study were already attracted to the experimental lamps from a much greater distance. At present, radar seems the only feasible option to study long-range responses of birds during the night. Future field experiments on the impact of bird-friendly lighting on nocturnally migrating birds

Fig. 5. 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 our observation period.



would do well to include the use of radar in their experimental setup.

From an applied perspective, the main conclusion that can be derived from this experiment is that birds do respond significantly differently under field conditions to various colors of artificial light, i.e., reactions of migratory birds to artificial light are largely determined by the wavelength characteristics of the light source. Migratory birds react strongest to white and red light (long wavelength); little to green light (shorter wavelength); and blue light (short wavelength) hardly causes any observable effect on the birds' orientation. Birds apparently did not react to the infrared heat radiation > 680 nm.

This led to the assumption that the visible long-wavelength part of the spectrum (excluding the infrared part) causes the disorienting effect on migrating birds. White light contains all parts of the spectrum (including long wavelengths), our red-light source only contained a small fraction of the long-wavelength part of the spectrum, and our green-light source contained very little long-wavelength radiation, whereas the blue-light source did not contain visible long-wavelength radiation at all.

Based on the results of the experiment presented here, it can be suggested that changing the color (spectral composition) of artificial lights for public

Table 4. Tests of all two-way and three-way partial associations involving reaction of the birds (REACT) in the fully saturated hierarchical log-linear model with generating class COLOR*MOON*CLOUD*REACT.

| Effect name | Partial χ^2 | df | P |
|-------------------|------------------|----|--------|
| COLOR*MOON*REACT | 3.26 | 3 | 0.354 |
| COLOR*CLOUD*REACT | 1.50 | 3 | 0.682 |
| MOON*CLOUD*REACT | 3.59 | 1 | 0.058 |
| COLOR*REACT | 154.62 | 3 | <0.001 |
| MOON*REACT | 0.94 | 1 | 0.331 |
| CLOUD*REACT | 11.29 | 1 | <0.001 |

roads and on human-built structures will significantly decrease the number of casualties among nocturnally migrating birds. Therefore, as a follow-up, the electronics company Philips experimentally developed bird-friendly light sources, low in red. It was not possible to include only blue light, even though this would seem optimal from the point of view of the birds. The problem is that humans cannot work safely under blue light. Therefore, the newly developed light source includes the green spectrum and appears greenish to human observers. We replaced the lights of the offshore gas-production platform L15 with these new bird-friendly light sources in autumn 2007. Figure 6 shows that the platform is sufficiently visible from a distance with the new lighting and so far the crew of the platform has not filed complaints about the new working conditions. In fact, an unexpected added bonus of the newly developed bird-friendly lamps is that the platform crew stated that they were less blinding and increased contrast vision during crane operations. Preliminary observations also suggest that far fewer birds are attracted to the platform (van de Laar 2007). Just how strong the reduction is remains to be determined.

Our study has initiated new research on the effects of artificial lighting on migrating birds and the possibilities of the further development of bird-friendly artificial lighting that would still be safe for humans to work with. This light will lack the long-

wavelength part of the spectrum and will thus be seen as greenish by human eyes. Additional advantages of using such a new type of lighting are improved contrast due to the high sensitivity of the human eye for the green part of the spectrum, better reflection on (green) roadside vegetation, and potentially less disturbance of natural vegetation (flowering, seed setting, and germination) by affecting the red:far-red ratio (see, e.g., Pons 1986).

The concept of bird-friendly lighting can potentially be used everywhere, both off- and onshore, artificial night lighting affects migrating birds. Examples include marine ports, coastal refineries, industrial areas, highways, airports, etc. However, as the recent book on ecological consequences of artificial night lighting edited by Rich and Longcore (2006) abundantly proves, migratory birds are not the only species harmed by artificial night lighting. What is needed now are systematic investigations into the impact of bird-friendly light on other organisms than birds. In the case of oil platforms in the North Sea, for instance, the possibility that migratory fish and sea mammals are also affected cannot be ruled out. The question we now face is whether it is possible to develop light sources that satisfy human demands, yet do not harm the ecosystem in general.

Fig. 6. Photo of the Nederlandse Aardolie Maatschappij (NAM) offshore gas-production platform L15, situated in the North Sea about 20 km offshore of the barrier island Vlieland (photo courtesy NAM), after our light-color recommendations were acted upon. At the time of the photo, some of the white lights still needed to be replaced by green lights.



Responses to this article can be read online at:
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