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UV Radiation as an Attractor for Insects

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Abstract—Light pollution due to exterior lighting is a rising concern. While glare, light trespass and general light pollution have been well described, there are few reported studies on the impact of light pollution on insects. By studying insect behavior in relation to artificial lighting, we suggest that control of the UV component of artificial lighting can significantly reduce its attractiveness, offering a strong ability to control the impact on insects. Traditionally, the attractiveness of a lamp to insects is calculated using the luminous efficiency spectrum of insect rhodopsin. This has enabled the development of lamps that emit radiation with wavelengths that are less visible to insects (that is, yellow lamps). We tested the assumption that the degree of visibility of a lamp to insects can predict its attractiveness by means of experimental collections. We found that the expected lamp's visibility is indeed related to the extent to which it attracts insects. However, the number of insects attracted to a lamp is disproportionally affected by the emission of ultraviolet radiation. UV triggers the behavior of approaching lights more or less independently of the amount of UV radiation emitted. Thus, even small amounts of UV should be controlled in order to develop bug-free lamps.

Keywords—UV radiation, insects, light pollution, light trespass, environment.

1 INTRODUCTION

Today, light pollution is a relevant issue in the subject of exterior lighting. The issue was first raised by astronomers; light pollution impairs astronomical observations and deprives people of the pleasure of contemplating the dark sky (the International Dark-Sky Association can be consulted for information on astronomical light pollution: www.darksky.org). A more recent concern is the impact of light pollution on ecosystems [Longcore and Rich 2004]. It has been

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shown that light pollution alters oviposition behavior in turtles, the trajectory of migratory birds, and the behavior of small mammals; additionally, light pollution has a strong impact on insects, as is stressed in the ample collective work edited by Rich and Longcore [2006]. These concerns have been addressed in a number of official reports and recommendations [Health Council of the Netherlands 2000; The Royal Commission on Environmental Pollution 2009; Huseynov 2010; IDA and IES 2011] and by some power companies with respect to the design of exterior lighting projects. For example, the Florida Power Company developed a manual for ecological lighting of the seacoast to protect sea turtles [Ernest and Martin 1998].

Although concerns about the effects of lighting on insect populations are quite recent, it has long been known that light attracts insects. Entomologists have spent years developing and perfecting light traps for epidemiological and agricultural surveys [see, for example: Hienton 1974; Szentkirályi 2002], but only in the last decade have studies begun to focus on the attraction potential of regular streetlights and its consequences [see, for example: Scheibe 1999; Kolligs 2000; Eisenbeis and Hänel 2009]. There are reasons to believe that night lighting has a significant effect on insect populations. Einsenbeis [2006], for example, estimated that the streetlights of a 240,000-inhabitant town in Germany may kill approximately 360 million insects per season. Considering that insects serve as pollinators for plants and food for a variety of other animals, this increased mortality could have broader effects. The attraction of insects to lights could also have effects on human health because it could provide a novel means of contact between human populations and disease vectors [Barghini and de Medeiros 2010].

To improve regulations and develop minimum-impact lamps, it is important to understand the causes of insect attraction to lights. Although the precise mechanisms are still controversial [see, for example: D'Arcy Thompson 1917; Verheijen 1958; Baker and Sadovy 1978; Janzen 1983; Nowinszky 2003], it has long been known that a key component that determines the attractiveness of a light source to insects is an emission spectrum ranging between ultraviolet and blue [Dethier 1963; Hollingswort and others 1968; Mazokhin-Porshnyakof 1969; Mikkola 1972; Hienton 1974; Blomberg and others 1976; Walker and Galbreath 1979; Worth 1979; Rea 1993; Service 1993; van Langevelde and others 2011]. Variability in attraction behavior, however, exists because attraction also depends on a number of other factors, one of which is the insects' main activity phase during the day [Rea 1993]. Diurnal insects are the least affected by light, but they may fly towards illuminated areas or UV lamps when disturbed [Lewontin 1959]. This is likely because such areas are presumed by the insect to be open areas into which it is suitable to fly. For nocturnal insects, attraction to light seems to result from navigational errors [Darcy Thompson 1917; Verheijen 1958; Mazokhin-Porshnyakov 1969; Nowinszky 2003]. During the night, insects navigate using celestial references. By keeping a constant angle to such a reference, the insect can fly in a straight path. If the reference happens to be a terrestrial light source, keeping a constant angle would result in an equiangular spiral path towards the light source. Because UV-green or UV-blue contrasts can be used to distinguish between celestial and terrestrial objects [Möller 2002], ultraviolet radiation is probably essential for a light source to be considered as a celestial reference or open space.

Based on this model, strategies to minimize insect attraction to lights are usually based on the spectral responses of insect photoreceptors. The 8th edition of the IES Handbook [Rea 1993], for example, follows the recommendation of Barrett and others, [1973, 1974] in suggesting the "maximum use of yellow-red light and the reduction of ultraviolet and blue" (p. 156), avoiding metal fixtures that may reflect polarized light, the use of directional fixture, and the suggestion that "an attracting lamp can be shaded so that its radiant output is directed downward and confined to [the] immediate area (p. 157)". Although the IES Handbook did not address this issue in later editions, this model is still generally followed in the design of "bug-free" lamps. Such lamps are usually designed to emit yellowish light because this is the region of the light spectrum that is least visible to insects. Similarly, electric fly killers can be enhanced with a UV-emitting lamp. In both cases, it is implicitly assumed that insects are attracted to lamps that are more visible to them. A recent report in which this assumption is also made is that of van Langevelde and others, [2011]; these authors correlated the mean lamp wavelength with the abundance and diversity of moths attracted as well as with their eye size.

More accurate quantification of the visibility of a lamp to an insect should take insect spectral sensitivity into account, but yellow bug-free lamps are indeed both less visible to insects and have a higher mean wavelength than UV-radiating insect attraction lamps. However, the attraction of a particular lamp for insects is not necessarily related to its visibility or to the mean wavelength it emits. Insects possess a variety of photoreceptors that are not used exclusively for color vision. Some stereotyped behavioral sequences, called wavelength-selective behaviors, are activated by a particular wavelength of light [Goldsmith 1990, 1994]. As reported by Goldsmith [1994:302], "The butterfly *Pieris* exhibits several different behavioral responses to colored lights, each with a distinct action spectrum exhibiting maximum sensitivity at different wavelengths: escape (A_{max} 370 nm), feeding (A_{max} 450 nm with a secondary maximum at 600 nm), drumming (A_{max} 560 nm), and egg laying (A_{max} 540 nm) [Scherer and Kolb, 1987]. Most of the spectral sensitivity curves are narrower than the absorption spectra of visual pigments, and with mixtures of 600 and 558 nm light, both feeding and drumming are inhibited by the presence of inappropriate wavelengths. The neural wiring thus appears to be more complicated than if each behavior were driven by a single spectral type of receptor." When perceived by an insect, UVA radiation could trigger a wavelength-dependent response to light attraction similar to what has been measured in frogs: "If the tendency of most species of frogs to jump towards a light is measured as in a forced choice experiment, short wavelengths (A_{max} 480 nm) stimulate positive phototaxis and longer wavelengths inhibit [phototaxis]." [Goldsmith 1994:303]. There is evidence that this does in fact occur. Insects become disoriented and less active inside greenhouses covered by UV-blocking polyethylene [Antignus 2000]. Moreover, when mulch (a protective cover placed over the soil to retain moisture, reduce erosion, provide nutrients, and suppress weed growth and seed germination) reflects UV radiation, there is a reduction in the population of insect pests [Kring and Schuster 1992]. In the former situation, the absence of UV radiation may disorient insects by creating a "skyless" environment so that an insect would not know where it is able to fly. In the latter case, UV reflection from below would result in an environment with "too much sky," that is, the insect's perception of too much space in which it is able to fly. Both of these examples indicate that UV radiation is used by insects to navigate while flying.

Based on the data presented above, it is generally accepted that UV radiation attracts insects. However, this apparent attraction could result from two distinct mechanisms. First, UV radiation might not have any special meaning to the animals and might be attractive only because most insects have a high sensitivity to light in this wavelength range (that is, UV radiation makes lamps more visible to insects). Alternatively, UV radiation may trigger wavelength-selective behavior that results in attraction to the light. It is important to distinguish between the two mechanisms. If the former holds, a reduction in light attraction would be achieved by reducing lamp radiation on all wavelengths to which insects are most sensitive. If the latter is more important, however, one should eliminate even the smallest amount of UV radiation in order to reduce attraction, and other wavelengths would be less important.

There have been no experimental studies that clearly distinguish the visibility to insects and the UV emission of a lamp while evaluating its attractiveness to insects. Our study aims to test whether UV radiation has a greater attractive power to insects than would be expected from its visibility alone.

2 MATERIALS AND METHODS

The test was conducted in a street surrounded by trees and isolated from urban lighting on the “Cidade Universitária” campus of the University of São Paulo. Static insect collecting traps similar to those used by Eisenbeis & Hassel [2000] were set up below lamps installed on seven-meter-tall lampposts.

Each treatment utilized a full cutoff lighting fixture as follows: Hg: 125 w mercury vapor bulb protected with tempered glass; Na: 70 w high-pressure sodium vapor bulb with tempered glass; Hg_F: 125 w mercury vapor bulb with tempered glass and a UV filter (Polycarbonate Lexan© 2 mm); Na_F: 70 w sodium vapor bulb with tempered glass and a UV filter (Polycarbonate Lexan© 2 mm); and T: trap without lamp, as a control setup. The radiance spectra of the bulbs were measured with a Monochromator Optronic 740A, an automatic wavelength drive (Optronic 740–1C) and a spectroradiometer (Photo Research OLISA-670). The transmittance of the UV filter was measured with a Hitachi U-3000 spectrophotometer.

The radiance spectrum of each treatment was calculated by multiplying the lamp irradiance by the filter transmittance. The visibility of each treatment to humans and insects was calculated by integrating the treatment radiance after multiplying it by the luminous efficiency spectra of the human eye (photopic vision) and of the rhodopsins of three-rhodopsin insects (represented by the sensitivity curve of *Apis mellifera*).

The collections were performed in two separate campaigns. The first used the Hg, Na, Na_F and T treatments and totaled 24 collections between March and June 2005; the second used all treatments and totaled 14 collections between March and April 2006. On each collection date, traps were set up before twilight and taken down the following morning. The collected insects were counted and identified to the order level. Ant and termite alates were discarded because a single nest in the surrounding area could significantly bias the results.

The mean insect counts were compared among treatments for both campaigns. The role of UV radiation in the treatments’ attractiveness was further tested by fitting the data to a generalized linear model using the visibility to insects, the date of collection and the presence of a UV filter as predictors of insect counts. Specifically, we tested whether accounting for the UV filter significantly improved the fit of the model or whether the treatment visibility was sufficient to explain its attractiveness. This model was adjusted only in the second collecting campaign, in which all treatments were used.

3 RESULTS

The number of insects collected varied greatly between collection dates, probably due to meteorological conditions and the lunar phase. Nevertheless, the number of collected insects was clearly higher in the Hg treatment than in the T

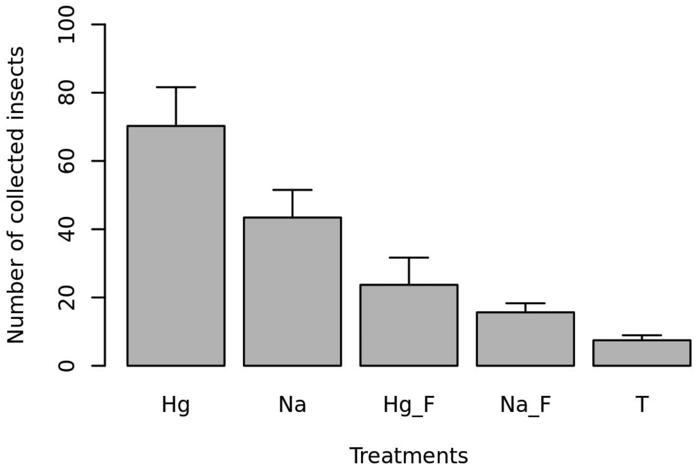


Fig. 1.
Mean values and 95 percent confidence intervals of the number of insects collected in each treatment.

treatment (Fig. 1). The same pattern was found for most insect orders when analyzed separately (Table 1).

Hg lamps have a strong UV component, a shorter mean wavelength and a higher visibility to insects than the other lamps tested. In contrast, only a tiny fraction of the emission of a Na lamp is in the UV range, and Na lamps are more visible to humans than Hg lamps but less visible to insects. The use of a UV filter only slightly affects the average wavelength of Na and Hg lamps or their visibility to humans but has a strong effect on the lamps' visibility to insects. The only lamp that has a UV/Green contrast similar to celestial objects is a Hg lamp; all others fall within the range of terrestrial objects as measured by Möller [2002] (Fig. 2, Table 2).

When the mean number of collected insects was considered with respect to the visibility of each treatment to insects, it became clear that these quantities are not entirely correlated. Specifically, treatments with UV filters collected fewer insects than would be expected from their visibility alone (Fig. 3). Indeed, a model that accounts for UV radiation fits the data significantly better than a model that ignores this variable (Table 3).

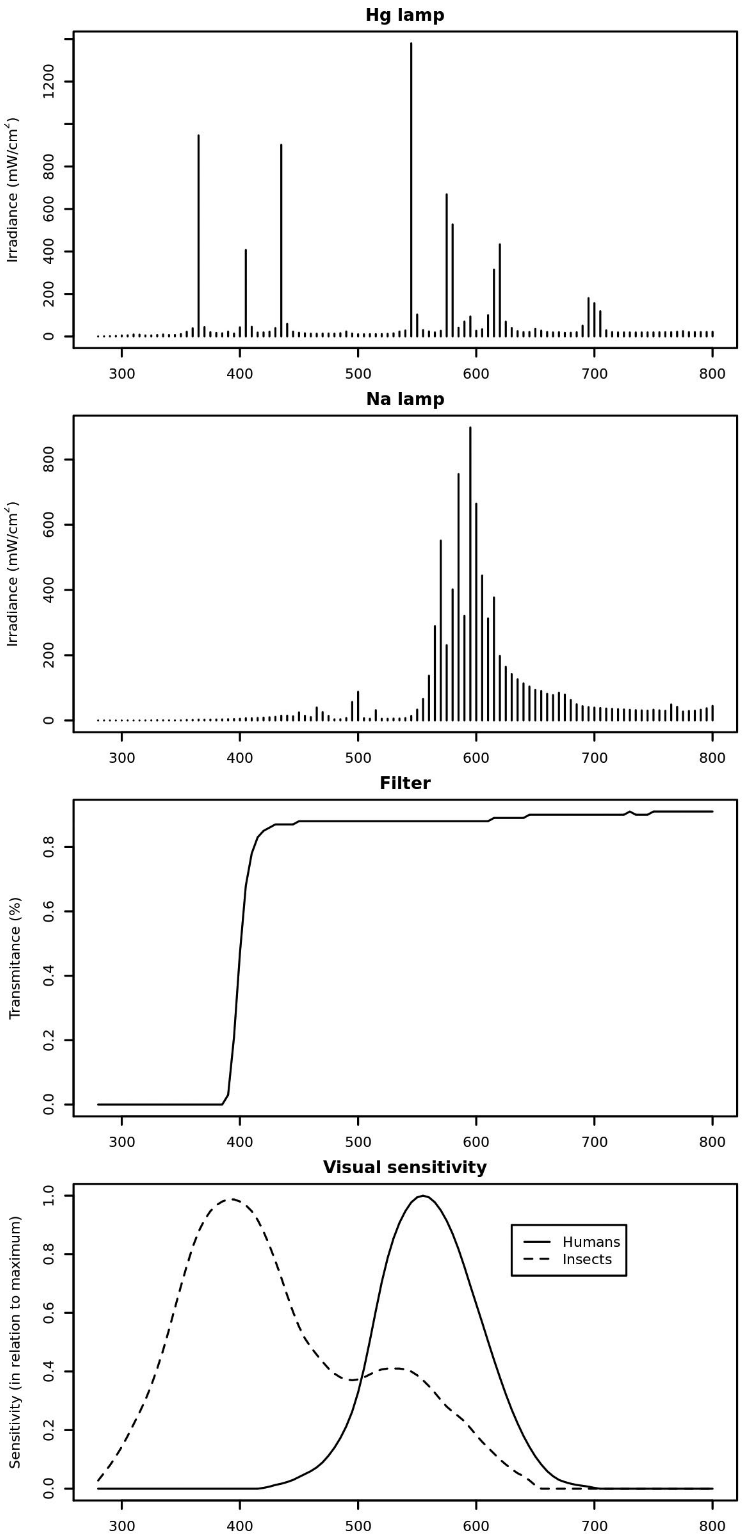
4 DISCUSSION AND CONCLUSIONS

Overall, our results confirm the general expectation from models currently in use by the illumination industry and suggest that "yellow" lamps are less attractive to insects than "white" lamps. This pattern was observed for most insect orders, with Coleoptera (beetles) and Diptera (flies and mosquitoes) being the most attracted to all treatments. Although our collections were performed in

Order	Hg	Na	Hg_F	Na_F	T
Diptera	25 ± 5.5	16.2 ± 4.4	9.6 ± 2.9	7.2 ± 2.7	1.9 ± 1.0
Coleoptera	18.4 ± 4.9	8.4 ± 2.7	5.3 ± 1.9	4.2 ± 2.0	1.9 ± 0.7
Hymenoptera	10.3 ± 3.2	6.2 ± 3.8	2.7 ± 1.4	3.1 ± 2.1	0.1 ± 0.1
Hemiptera	6.6 ± 2.1	4.3 ± 1.3	1.4 ± 0.7	2.9 ± 0.6	0.2 ± 0.1
Thysanoptera	5.6 ± 4.2	1.2 ± 0.6	0.6 ± 0.4	1.0 ± 0.4	1.6 ± 0.7
Lepidoptera	4.9 ± 1.7	1.1 ± 0.4	1.3 ± 0.4	0.6 ± 0.3	0.03 ± 0.05
Psocoptera	1.3 ± 0.5	1.2 ± 0.6	0.6 ± 0.3	0.7 ± 0.3	0.1 ± 0.1
Other	0.4 ± 0.2	0.2 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.0 ± 0.0

TABLE 1.
Mean ± 95% Confidence Interval of the Insect Counts in Each Treatment, Separated by Order. Hymenoptera does not include ants. "Other" includes the following orders: Blattodea, Dermaptera, Neuroptera, Orthoptera, Trichoptera and Strepsiptera

Fig. 2.
Irradiance spectra of the two kinds of lamp used in the test, the transmittance spectrum of the UV filter and the visual sensitivity curves used in the calculations. The horizontal axis is the wavelength (nm) for all curves.



Treatment	Visibility to Humans	Visibility to Insects	Average Wavelength (nm)	UV/Green Contrast
Hg	1	1	531	49.2
Na	1.33	0.44	607	−21.3
Hg_F	0.88	0.59	564	−37
Na_F	1.17	0.38	609	−19.7

TABLE 2.
Metrics Calculated from Radiance Spectra. Visibility is calculated relative to Hg. The average wavelength follows the calculation by Van Langevelde et al. (2011). The UV/Green contrast follows Möller (2002, Fig. 3). Negative values are usually found in terrestrial objects, while positive values are found in celestial objects

a tropical environment, a similar faunal composition was obtained in Germany [Enseibeis and Hassell 2000], thereby confirming the general applicability of the results. Additionally, we collected a very low number of moths (Lepidoptera), which are probably the most studied organisms in terms of attraction to light [see, for example: Mikkola 1972; Baker and Sadovy 1978; Worth and Muller 1979]. This could be a result of a bias in our traps toward smaller insects or of an already depleted moth fauna in the highly illuminated city of São Paulo. However, the taxonomic composition of our collections suggests that beetles and flies deserve more attention in studies of attraction to lights. Detailed data on insects of the different taxa that were collected available in the appendix of the doctoral thesis of the senior author of this article [Barghini 2008].

Numerous previous studies have found that light sources with higher wavelengths attract fewer insects, but none of these studies have compared the visibility of different lights to insects. Even if insect spectral sensitivity is taken into account, visibility alone is insufficient to explain the attractiveness of a lamp. As an example, the Hg F lamp is a white lamp that is more visible to insects than a Na lamp, yet it exhibited less attractiveness.

For both lamps tested, the use of a UV filter significantly reduced the number of insects despite the variation in UV content of the light emitted by the lamps. UV radiance is approximately 2 percent of the visible light radiance in sodium vapor lamps and 10 percent in mercury vapor lamps. Therefore, the striking effect found in both cases when a UV filter was used indicates that insect attraction does not depend only on the UV amount and lamp visibility. Even small amounts of UV radiation seem to be sufficient for an object to be identified as celestial, resulting in attraction. UV radiation, therefore, acts as a releaser for

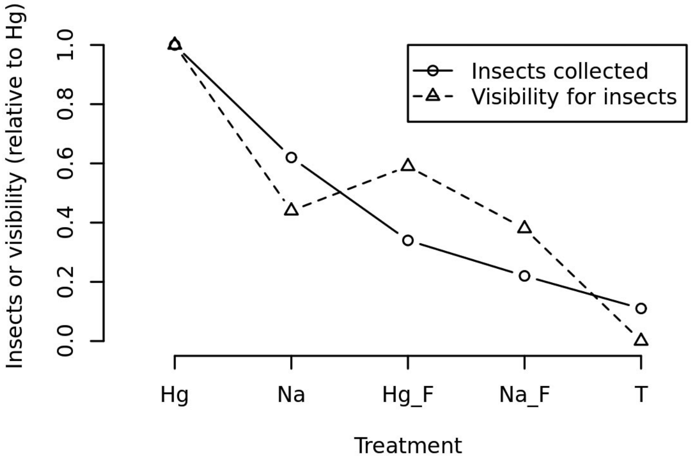


Fig. 3.
Number of insects collected and the calculated visibility to insects (relative to Hg) for each treatment.

TABLE 3.
Model Comparison by Analysis of Deviance. The full model contains the date, visibility to insects and the presence or absence of a UV filter as predictors of insect counts. The reduced model includes only the date and visibility. The P value was determined by a chi-square test

	Resid. Df	Resid. Dev.	Df. Deviance	P value
Full model	54	299.63		
Reduced model	55	398.54	−98.91	<0.001

insects, generating an attraction to artificial lights that is greater than would be expected based on the lamp's visibility alone. Our results fail to support the hypothesis that the presence of UV/Green contrast is fundamental for the recognition of a celestial object by an insect. Using the threshold in UV-green contrast found by Möller [2002], Hg lamps would indeed be considered celestial objects, but Na lamps would be classified as terrestrial. At least for nocturnal insects, the absolute emission of UV above a threshold may be more important than its contrast to other colors in triggering attraction behavior.

Our findings provide an important tool for the design of minimum impact lighting systems. As such, our findings support those of Eisenbeins [2006], who advocated the use of UV filters for streetlights. It is highly advisable that studies on lamp attractiveness to insects take into account not only the lamp's visibility and average wavelength but also the lamps' radiance of even minimal amounts of UV radiation. The wavelength threshold that activates insect attraction behavior remains to be identified. While we have found that reducing UV emission to below 400 nm is effective, it is possible that reducing the emission to below a higher wavelength [for example, 480 nm] may have an even greater effect with minimal consequences for human vision. Studies that take this information into account will enable the lighting industry to develop both environmentally friendly and highly effective lighting systems.

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