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Long-Term Comparison of Attraction of Flying Insects to Streetlights after the Transition from Traditional Light Sources to Light-Emitting Diodes in Urban and Peri-Urban Settings

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Abstract: Among the different light sources used for street lighting, light-emitting diodes (LEDs) are likely to dominate the world market in the coming years. At the same time, the spectral composition of nocturnal illumination is changing. Europe and many other areas worldwide have implemented bans on energy-inefficient lamps, such as the still very common mercury vapor lamps. However, the impact of artificial light on insects is mostly tested with light-traps or flight-intercept traps that are used for short periods only. By comparing the numbers of insects attracted by street lamps before and after replacing mercury vapor light sources (MV) with light emitting diodes, we assessed the impact in more typical (urban and peri-urban) settings over several years. We found that LED attracted approximately half of the number of insects compared to MV lights. Furthermore, most insect groups are less drawn by LED than by MV, while Hymenoptera are less attracted by MV than by LED. Thus, the composition of the attracted communities differed between the light sources, which may impact ecosystem processes and functions. In green peri-urban settings more insects are attracted than in an urban setting, but the relative difference between the light sources is the same.

Keywords: artificial light; Hymenoptera; LED; Lepidoptera; mercury vapor; moths; phototaxis

1. Introduction

Illumination of nocturnal landscapes has increased rapidly during the last few decades [1,2] and is considered an important ecological threat [3–5]. One of the best known impacts of artificial light at night (ALAN) is the attraction of insects by light sources and this has been recognized as a potential threat for a long time [6]. Given the recent decline in insect populations, the ongoing spread of ALAN and the current worldwide transition from energy-inefficient traditional light sources to energy-efficient LED, a better understanding of the impact of different light sources is needed [3,7].

Different light sources attract different numbers of insects and to a large extent this depends on the spectral composition [8–10], therefore several studies comparing the attractiveness of lamp types differing in spectral output have been performed and in general light sources that emit a large amount of UV and blue light attract more insects than light sources that emit mostly longer wavelengths [9,11,12]. Most of these studies, however, focus on moths, a big and important group but only one of the many groups of insects being affected by ALAN. Different insect orders have different photoreceptors in their eyes and therefore have different spectral sensitivities [13]. The results for moths are thus not directly transferable to other insect orders [8]. Some spectra might have a reduced impact for one insect order while impacting another insect order more strongly.

Another complicating factor is that most studies use light traps. While this is ideal for a number of insects, it is unclear whether the assemblage in these traps reflects what is attracted by streetlights. Light traps are typically placed on the ground with the light source close to the ground, while street lights are at least several meters above the ground. This might very well have a selective effect, as the angle under which the insect is exposed is different. This means that different ommatidia are exposed and the ommatidia in different parts of the eye frequently do not have the same spectral sensitivity [14]. Light traps are also deployed for one or a few nights, while normal street lights typically illuminate nocturnal landscapes over a period of several decades. Whether these substantial differences affect which species are being attracted is hardly known. One study uses lamp post like structures [12] with metal halide and sodium vapor, but only looked at direct effects, changing the configuration each night. Wakefield et al. [15] compared the attraction of LED based lighting systems with other traditional lighting systems using actual lamp posts but did so by placing streetlights on poles in a study site for a few nights, thereby focusing on the initial effects.

Most studies on the attraction of insects to artificial light test the effect in a semi-natural setting where other artificial light and anthropogenic disturbance is limited [16]. Most light sources are, however, applied in urban and peri-urban settings and not in semi-natural areas. We are not aware of any study where the insect phototaxis of different light sources in urban and peri-urban areas is explicitly compared. Therefore, it is currently unknown to what extent this context changes the ecological impact of ALAN. Furthermore, whether there is a difference between light sources is dependent on the landscape context has not been investigated. The insect community in urban areas is not the same as that in natural areas and might be selected to be less sensitive to ALAN [17] therefore an observed difference in impact of different light sources in semi-natural habitat might not be representative for an urban context.

Currently, many streetlights are being replaced with light-emitting diodes (LED). In some cases these are retrofitted, with an LED in the original luminaire and sometimes the entire streetlight is replaced. Mercury vapor lamps (MV) have been phased out since April 2015 as per EU Regulation 245/2009, so that it can be expected that their 23% share of EU28 road lighting in 2015 will probably drop to 0%. On the other hand, new sales of road lighting lamps and luminaires have been dominated by LED technology since then and so their 4% share in 2015 will increase significantly in the next few years [18]. Also in Berlin and Brandenburg, many mercury vapor lights were used until recently and these are being replaced by LED. This transition from mercury vapor to LED allows us to assess to what extent the lamp type affects the number and the assemblage of insects attracted to streetlights and whether this depends on the setting, either peri-urban or urban, using actual street lighting in a realistic long-term setting. Mercury vapor is known to be extremely attractive for insects, as a result of the UV emissions it produces, while LED attracts much fewer insects. In a study using light traps in a semi-natural setting MV attracted 7 times as many insects as a white LED with a similar luminous flux [8].

To test whether there are qualitative and quantitative differences in the attraction of insects to LED and MV when used in streetlights, we attached flight intercept traps to street lights that produce neutral white light at similar light levels and sampled the attracted insects. As the replacement was not simultaneous, we can separate the difference between years from that of the lamp type. Most streets that were sampled were in a green peri-urban setting (Schulzendorf, Germany, adjacent to Berlin), while one was in the city center of Berlin, Germany. We can therefore assess whether the setting affects the ways that the two light sources attract insects, both in terms of the number of insects attracted as well as the composition of the catches.

2. Materials and Methods

From 2011 until 2013, we sampled insects that were weekly collected around street lights from the end of June until early October. Which streets were sampled in each year and which light sources were used is given in Table 1. Flying insects were collected using air eclector traps consisting of two perpendicular acrylic panels (each 204 mm × 500 mm × 3 mm) mounted above a collecting funnel and placed 0.5 m below each lamp. Below the funnel, a bottle with alcohol was mounted. Insects were collected and identified to the family or order level. In 2011 (Leibnizstraße and Jahnstraße) and 2013 (Leibnizstraße, Jahnstraße and Brandenburger Straße) insects were sampled diurnally as well. Light intensity at ground level was measured during new moon nights using a luxmeter (International Light Technologies ILT1700 Peabody, MA, USA) (Table 2). Spectral composition was measured using a spectro-radiometer (JETI Specbos 1211 UV, Jena Technische Instrumente, Jena, Germany) (Figure 1, Supplementary Materials Figure S1). For the nocturnal samples a total of 6718 flying insects were caught over 545 sampling events (a trap for one night, Table 1). For the diurnal samples, there were 255 insects over 92 sampling events.

Table 1. Number of sample-events per location per lamp type for the different locations and lamp types (light-emitting diodes – LED, mercury vapor – MD).

Location	Light Source	Year	Sample-Events
Urban (Berlin city center)			
Leibnizstraße north	MV	2011	44
Leibnizstraße south	MV	2011	44
Leibnizstraße north	MV	2012	56
Leibnizstraße south	LED	2012	56
Peri-urban (Schulzendorf)			
Jahnstraße	MV	2011	112
Jahnstraße	MV	2012	60
Jahnstraße	LED	2012	60
Brandenburger Straße	LED	2012	60
Brandenburger Straße	LED	2013	39
Helgolandstraße	LED	2013	33
Jahnstraße	LED	2013	73

Table 2. Light sources, mean illuminance at ground level, color temperature of the light, and height of the lamp above the ground.

Location	Light Source	Mean Illuminance (lx)	Mean Correlated Color Temperature (k)	Mean Height (m)
Urban (city center Berlin)				
Leibnizstraße north	MV	9.6	4290	10.0
Leibnizstraße south	MV	9.1	3700	10.2
Leibnizstraße south	LED	9.5	3650	10.2
Peri-urban (Schulzendorf)				
Jahnstraße	MV	10.2	4650	4.1
Jahnstraße	LED	18.6	4036	4.1
Brandenburger Straße	LED	17.5	3360	4.9
Helgolandstraße	LED	7.2	2990	4.4

Total number of insects was analyzed using a GLMM with negative binomial error distribution as well as an urban/peri-urban setting and a light source, along with their interactions, as fixed effects. The location and year were analyzed as random effects, while the light level in lux was included as a covariable in the analysis. This model was tested with a Z-test and a $p < 0.05$ was considered to be significant.

In order to investigate whether the two light sources merely differed in the strength of the attraction or also in the relative attractiveness for different groups of insects, we conducted a community analysis.

Compositional differences among samples were computed as Bray-Curtis dissimilarities (Beals 1984). We standardized the dataset using a chord transformation in order to reduce the influence of common taxa (Legendre and Gallagher 2001) in the assessment of differences in community composition. For the comparison of the numbers attracted by the light sources, no transformation was used because this complicates interpretation. A two-way Permutational Multivariate Analysis of Variance (perMANOVA) was used to test for compositional dissimilarity among "light sources" and "habitat" including their interaction. A SIMilarity PERcentage (SIMPER) analysis (Clarke 1993) was used to assess which taxa contributed to the dissimilarity of the communities (after one-way perMANOVA, see Supplementary Materials Table S1). We used a non-metric multidimensional scaling (NMDS) plot to visually assess differences in taxonomic composition.

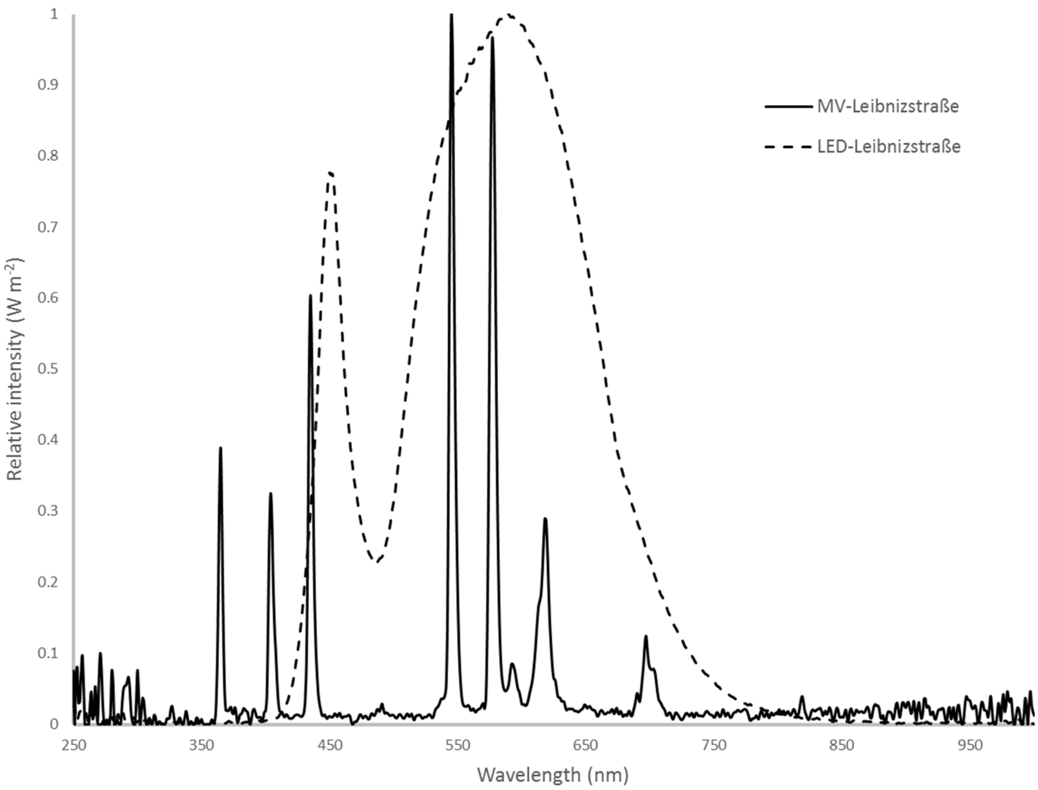

Figure 1. Spectral composition of both light sources used in Leibnizstraße - LED and mercury-vapor - as an example for different spectral compositions at a similar correlated color temperature (neutral white light around 4000 K). Graphs are standardized to a peak of 1.

3. Results

Replacement of MV with LED reduced the number of insects caught in the traps at night ($Z = 3.369$, $p < 0.001$) and the number of insects attracted differed between urban and peri-urban area ($Z = -4.607$, $p < 0.001$) (Figure 2). There was, however, no interaction between habitat and light source in the number of insects attracted ($Z = 0.218$, $p = 0.828$). The light level on the ground did not have a significant effect ($Z = -0.123$, $p = 0.902$) on the number of insects caught in the traps.

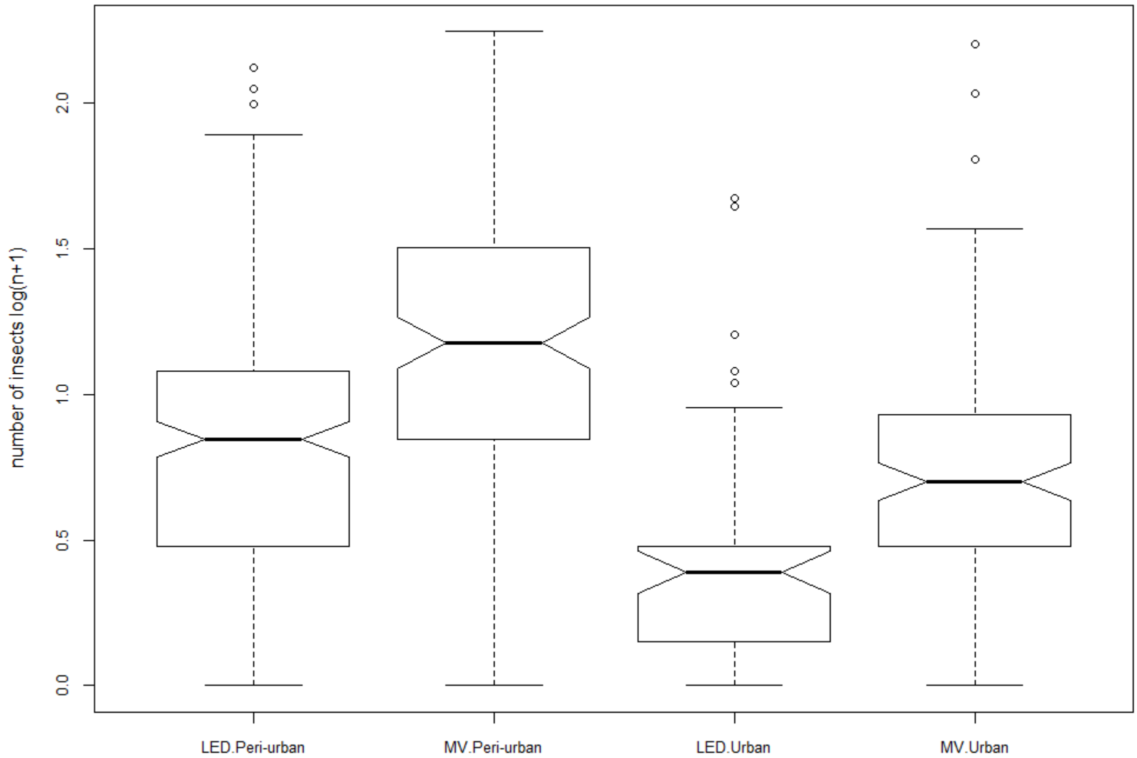

Figure 2. Boxplot of number of insects caught per night on a 10-log scale with median, quartiles, and whiskers indicating the highest and lowest value within a 1.5 interquartile range and circles indicating values outside this range. To prevent zero results, 1 was added to all of the samples.

For the diurnal samples, there was a difference between urban and peri-urban settings ($Z = -2.650$, $p = 0.004$), a trend to higher numbers of flying insects in the traps with MV than with LED $Z = -1.739$, $p = 0.08$, and a trend to larger differences between the lamp types in urban than in peri-urban areas ($Z = 1.696$, $p = 0.09$).

The communities attracted are markedly different between the two lamp types. ($F_{1,495} = 9.7665$, $p < 0.001$) and, as to be expected, between urban and peri-urban areas ($F_{1,495} = 37.668$, $p < 0.001$) (Figure 2). However, there is no interaction between the two factors, thereby indicating that they act independently ($F_{1,495} = 0.953$, $p = 0.61$). The diversity in the traps with LED and MV did not differ as the multivariate dispersion is homogeneous ($F_{1,497} = 3.3618$, $p = 0.067$).

The simper analysis identified Diptera (27% of variation, 2.4 as many in MV as in LED), Hemiptera (26%, 2.4 x), Hymenoptera (13%, 0.6 x), and Lepidoptera (11%, 1.5 x) as the major drivers of the dissimilarity (Supplementary Material Table S1, Figure S2).

4. Discussion

There is a clear difference in terms of attraction of insects between LED and MV, confirming that the divergence shown in previous studies also applies to a more typical setup with streetlights. This difference is independent of the environment as the relative difference is the same in a city center as in a green peri-urban environment. This means that the results from studies comparing different lamp types in less urban areas are probably also valid for more urbanized areas, where most light is used. The lower catches in urban areas can be explained by the lower proportion of green areas. Furthermore, some adaptations to ALAN, such as a reduction in flight-to-light behavior can be expected for at least some species, in particular those with short generation times and in areas with a longer illumination history [5,17]. There is no effect of light intensity at ground level, but the setup was designed to have light levels that are very similar for the different locations and treatments and to, thus, exclude this effect. It is very likely that with larger variation in light levels it would become important. The light sources are comparable in both light level and color temperature (Table 2), but differ strongly in spectral composition (Figure 1, Supplementary Materials Figure S1). The diurnal catches show an expected difference between urban and peri-urban setting but no clear difference between lamp types. There was a trend towards more insects at the MV-lights during daytime. This might be caused by insects that are attracted at night and accumulate in the surrounding environment. There is also a trend towards greater interaction, with the difference being larger in peri-urban areas. Especially in the well wooded peri-urban areas, it is likely that insectivorous predators such as the abundant great and blue tits (*Parus major* and *Cyanistes caeruleus*) may benefit from the presence of exhausted or dead insects that were attracted to the lights during the night. This has also been described, for example, for carrion beetles and slugs [16,19].

At night most groups of insects are less attracted by LED than by MV, but the difference between the two light sources is not the same for each group and in contrast to our expectations, some were more frequent in the traps at LEDs. Diptera are much more attracted by MV than by LED while Hymenoptera are relatively less attracted by MV than by LED. This results in significantly different composition of insects attracted by the LED and MV although the diversity of the catches is identical. This means that a shift from MV to LED will not only reduce the impact on the insect community as a whole, but might also shift the interaction between species groups. For instance, moths might increase in abundance as they are affected less by LED, but they might additionally experience a reduction in parasitation [20] as hymenoptera are affected more strongly by LED. How this cascades through communities is unknown.

The impact of artificial light extends beyond attraction of insects to light sources. Light can affect immune responses [21], predator avoidance [22] and interactions with plants [23,24]. Moths reduce nocturnal activity when illuminated, this has been shown to affect pheromone production [25], mating [26], and feeding behavior [27], and shorter wavelengths seem to have a stronger impact that is similar to attraction [10,28]. Long wavelength light was also found to have an effect intermediate between the dark control and, white and short wavelength light on several life history decisions in moths [29]. This suggests that spectral sensitivity for attraction and other ecological impacts of ALAN on insects is similar. This would mean that the advantage of replacing MV with LED extends beyond attraction and might also directly reduce impact on ecosystem services such as pollination [30,31]. In Lewanzik and Voigt [32], the hunting activity of Pipistrelle bats was 45% less for pipistrelles with LED than with MV, which is in agreement with the general pattern that is found for long versus short wavelength light [33,34]. Some bat species, such as pipistrelles hunt for insects attracted to light sources while other species, such as *Myotis* species, avoid illuminated areas. As these bats feed on insects, this might indirectly affect local insect communities.

The transition from traditional light sources to LED is often seen as being positive for ecology, as the light sources that emit UV such as MV and other metal halide lamps will be replaced by a light source that does not and therefore attracts less insects as has been shown using light traps. The results from this study confirm this conclusion using a more typical setup with the light mounted on a pole. However, the effect was much smaller than found in a study using light traps. In the study by van Grunsven et al. [8] a 7-fold difference between MV and LED is described while in our study it is less than 2-fold. There are several possible explanations. The LEDs have a different spectral composition and thus might be more attractive [11]. The fact that the lamps were on poles and not placed close to the ground might have an effect. Finally, these street lights are on every night and not only for a few nights as is standard for light traps, meaning the MV lights might have exhausted the local nocturnal insect population [35] and in turn resulting in lower catches. In contrast, Plummer et al. [36] suggest that streetlights increase the local density and diversity of moths. They found a higher abundance and diversity of moths in gardens closer to streetlights, in areas with a higher density of streetlights and with streetlights with wider spectra and in particular UV emissions. The mechanism behind this effect is, however, unclear as in general attraction to light is thought to work predominantly on short distances of up to 30–50 m [37,38]. Overall, we can conclude that (i) the change from MV to LED does reduce attraction of nocturnal insects substantially, that (ii) this is the same in urban and peri-urban settings, and that (iii) the benefit does differ between groups of insects.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/22/6198/s1, Table S1: Relative contribution of the drivers of dissimilarity, Figure S1 Spectral output for the different light sources and Figure S2 Relative contribution of the different insect orders.

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