A new LED lamp for the collection of nocturnal Lepidoptera and a spectral comparison of light-trapping lamps

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Abstract. Most nocturnal Lepidoptera can be attracted to artificial light sources, particularly to those that emit a high proportion of ultraviolet radiation. Here, I describe a newly developed LED lamp set for the use in the field that is lightweight, handy, robust, and energy efficient. The emitted electromagnetic spectrum corresponds to the peak sensitivity in most Lepidoptera eye receptors (ultraviolet, blue and green). Power LEDs with peaks at 368 nm (ultraviolet), 450 nm (blue), 530 nm (green), and 550 nm (cool white) are used. I compared the irradiance (E_e) of many commonly used light-trapping lamps at a distance of 50 cm. Between wavelengths of 300 and 1000 nm, irradiance from the new lamp was 1.43 W m^{-2}. The new lamp proved to be the most energy efficient, and it emitted more radiation in the range between 300 and 400 nm than any other lamp tested. Cold cathodes are the second most energy-efficient lamps. Irradiation from fluorescent actinic tubes is higher than from fluorescent blacklight-blue tubes. High-wattage incandescent lamps and self-ballasted mercury vapour lamps have highest irradiance, but they mainly emit in the long wave spectrum. The use of gauze and sheets decreases the proportion of UV radiation and increases the share of blue light, probably due to optical brighteners. Compared with sunlight, UV irradiance is low at a distance of 50 cm from the lamp, but (safety) glasses as well as keeping sufficient distance from the lamp are recommended. In field tests, the new LED lamp attracted large numbers of Lepidoptera in both the Italian Alps and in the Peruvian Andes.

Introduction

Light-trapping has long been known as an efficient method for collecting of nocturnal insects in general and Lepidoptera in particular (e.g. Taylor and French 1974; Holloway et al. 2001; Infusino et al. 2017). Early on, it was observed that moths can be attracted to the light of fire or candle-light and might even get burned – the family name Pyralidae probably relates to this observation (Emmet 1991). Light-trapping, either manual or with automatic traps, has become a standard and widespread method in ecology, taxonomy, and Lepidoptera monitoring schemes, and it is supposed to represent the only method allowing a large number of clades to be sampled quantitatively in large numbers (Holloway et al. 2001). Light sources with a high proportion of ultraviolet (UV) radiation tend to attract a greater number of individuals and more taxa (van Langevelde et al. 2011). A research focus in recent years has been to investigate the impact of modern street lighting on insects ("light pollution": e.g. Huemer et al. 2011; van Langevelde et al. 2011; Somers-Yeates et al. 2013; Pawson and Bader 2014; van Grunsven et al. 2014; Macgregor et al. 2016), including implications of anthropogenically driven selection on flight behaviour in urban areas (Altermatt and Ebert 2016).

A wide range of lamp and trap types for light-trapping has been used in entomological research. Although standardisation is desirable, the availability of new designs and lamps has continually led to changes in the lamp set-ups used. Depending on the requirements of research, it is (a) either more important to stress continuity and use a standard method that has been used in previous studies, or it is (b) more important to apply the most efficient and best available technology. A good example of (a) are Rothamsted traps (Williams 1948) that are operated with strong incandescent lamps with a tungsten filament. The use of this 'old-fashioned' technology can be justified in long-term monitoring programmes that are intended to be continued without a substantial methodological change (Southwood et al. 2003). Established methods such as the use of incandescent or high-pressure mercury vapour (MV) self-ballasted lamps also offer the advantage of long-term experience and published comparative studies on their performance (e.g., Intachat and Woiwod 1999).

The use of established light trapping methods does, however, have some disadvantages. For example, incandescent lamps have largely been abandoned in Europe because they are primarily producing long-wave radiation including a large proportion of invisible infrared radiation (Fig. 5a) that contributes relatively little to attracting insects (e.g. Cowan and Gries 2009), while the lifespan of such lamps is rather limited (Infusino et al. 2017). MV lamps emit a more favourable spectrum of radiation (Fig. 5a), but the longevity of the commonly employed self-ballasted type is similarly limited as incandescent lamps (Infusino et al. 2017). Moreover, high pressure MV lamps are being phased out due to their content of toxic mercury, which is banned by new legislations in many countries. Both types of lamps require high voltage, which means that during field work heavy and bulky generators are required. Despite containing mercury, fluorescent tubes of all types are still widely used (e.g. 'energy-saving lamps'). For insect collectors, particularly popular types of fluorescent tubes emit large proportions of UV radiation, including actinic / blacklight (BL) tubes as well as blacklight-blue (BLB) tubes – the latter with a dark-blue filter coating that absorbs most light. More recently, cold cathodes have become available through their use as backlighting of monitors and as decorative illumination in computer cases. These vary in their wavelengths and one can therefore choose those that include the UV range. However, little seems to be known about their performance in light-trapping so far. The use of LEDs is now increasingly common in light-trapping (Green et al. 2012; Price and Baker 2016; Infusino et al. 2017). LEDs have also been employed in experimental studies because a wide range, with different radiation peaks, is available (e.g. Cowan and Gries 2009; Kadlec et al. 2016).

Although lamp emission data are sometimes provided by the manufacturers, standardized comparisons of the emission or irradiation of different lamps are rare in the entomological literature. A comparison of six light sources with an emphasis on street lighting was given by van Grunsven et al. (2016). Papers can also easily be overlooked if published in journals or in languages with limited readership, as exemplified by a paper by Steidel and Plontke (2008) that graphically shows the qualitative emission spectra of various lamps.

Here, I describe a new LED lamp design intended for use in light trapping under field conditions, including remote tropical locations. The lamp was developed with the aim to minimize weight and size and to maximize energy efficiency and longevity. The aim was to be able to power this lamp with cheap and widely available 5 V lithium batteries ('powerbanks'), as well as the option of using 12 V batteries. Overall emission was intended to be of comparable or higher quantity

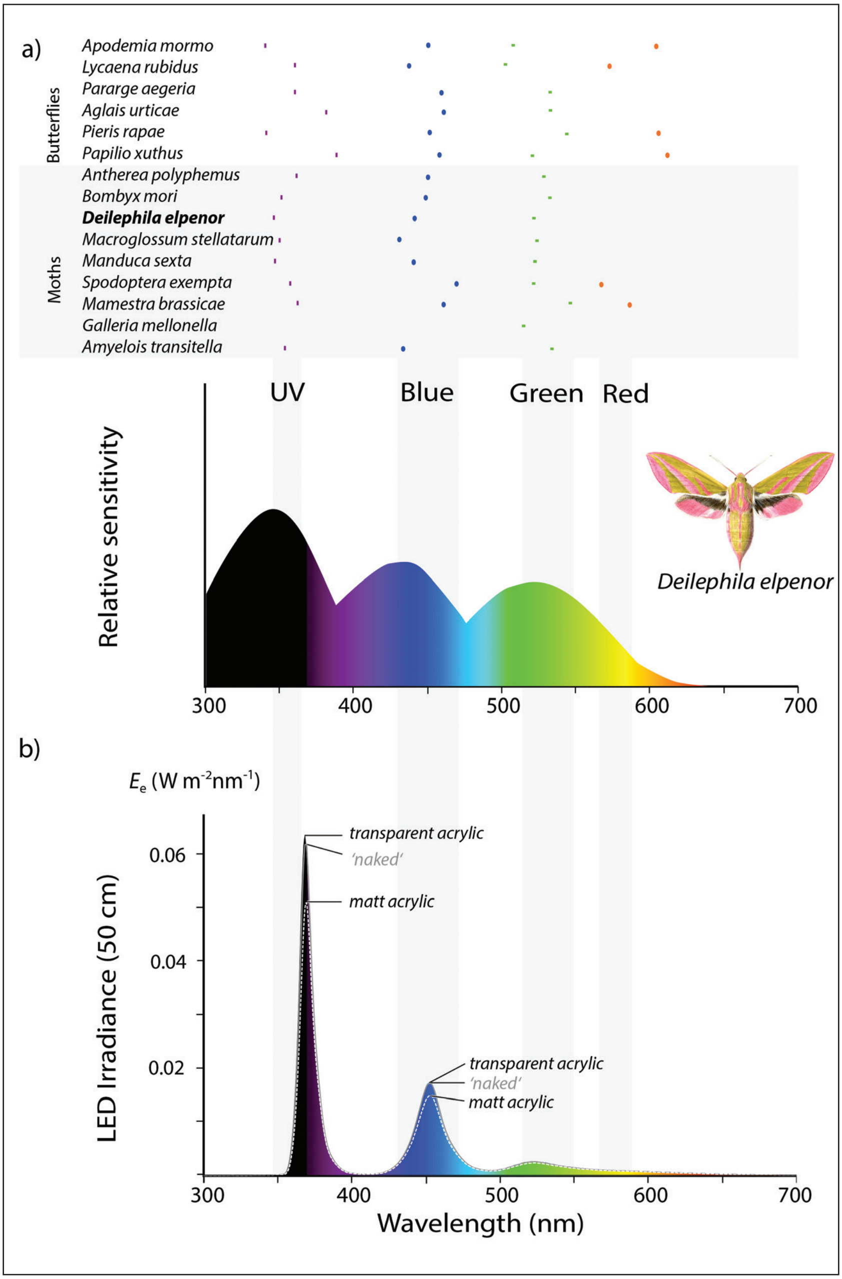

Figure 1. a. Values of maximum spectral sensitivity of Lepidoptera eyes, modified from Briscoe and Chittka (2001) and Johnsen et al. (2006), and sensitivities of the photoreceptors of the hawk moth *Deilephila elpenor* as an example, with peak absorption wavelengths of 350, 440, and 525 nm (Johnsen et al. 2006). **b.** The spectral composition of the new LED lamp (operated at 350 mA) is oriented towards the spectral sensitivity of moth eye receptors (background grey bars). A transparent acrylic cylinder has only a minimal influence on the irradiation from the lamp whereas a matt acrylic cylinder (dashed white line) slightly decreases the performance of the lamp, see also Table 1.

than fluorescent BL and BLB tubes used in many previous field studies (e.g. Brehm and Axmacher 2005), and to provide a higher output than in previously described LED-based designs (Green et al. 2012; Price and Baker 2016; White et al. 2016; Infusino et al. 2017).

The spectral composition of the lamp is orientated towards the peak sensitivity of lepidopteran eye receptors as suggested e.g. by Steidel and Plontke (2008), Mobbs (2016), and Price and Baker (2016). The available data on lepidopteran eye receptor sensitivity is still limited but includes a broad range of taxa (Briscoe and Chittka 2001, Fig 1a). These data suggest that three types of receptors are commonly found in moths, exemplified in the hawkmoth *Deilephila elpenor* (L.) (Johnsen et al. 2006): one in the ultraviolet, one in the blue, and one in the green range (Fig. 1a). *Synanthedon myopaeformis* (Borkhausen) (Sesiidae) is sensitive both in the ultraviolet and green range (Eby et al. 2013). Further receptors can be present and are possibly even widespread, such as red receptors known from the noctuids *Spodoptera exempta* (Walker) and *Mamestra brassicae* (L.) (Fig. 1a). As an extreme case, photoreceptors of 15 distinct spectral sensitivities were found in the butterfly species *Graphium sarpedon* (L.) (Papilionidae) (Chen et al. 2016). Given the large empirical success of lamps with a high proportion of UV radiation (including MV lamps, fluorescent tubes, cold cathodes, and UV LEDs), the emission of this short wave radiation was considered to be particularly important.

The emission of the new lamp is described in detail and quantitatively compared with a range of lamps commonly used by entomologists. Measurements include transparent clear and matt protective acrylic glasses, sheets, and gauze. Lamp emissions at different distances are compared with sunlight and the roles of spectacles and sun spectacles as eye protection are discussed briefly. Finally, the new LED lamp was tested under field conditions in more than 50 sampling events in the Italian Alps and Peruvian Andes, to confirm that nocturnal Lepidoptera were indeed attracted to the lamp and opening perspectives for further research.

Material and methods

Lamp design

The outer shape of a cylinder was considered as the best choice, not least because this allows the use of the lamp within existing trap designs. Power LEDs with a maximum power consumption of 3 W were chosen because they are generally more energy efficient than Power LEDs ≤ 1 W as found for example in LED stripes (White et al. 2016; Infusino et al. 2017). On the other hand, LEDs with higher wattage (e.g., 5 or 10 W) were not considered since this would have easily surpassed the desired maximum power consumption of ca. 15 W. Irradiance from a number of different LEDs was measured (see below, Appendix 1) and those with the best performance were chosen. LEDs with different wavelengths were used in order to reflect different sensitivity peaks in moth eye receptors (Fig. 1), with an emphasis on short wave radiation (UV and blue). For the final lamp design, eight Power LEDs on star circuit boards were arranged at two levels, each separated by 90° (Fig. 2). Four UV LEDs (SSC Viosys UV CUN66A1B), two Cree XP-E2 Royal Blue LEDs, one Cree XP-E2 Green LED, and one Cree XP-L V6 Cool White LED were finally selected. LEDs were glued with a thermal adhesive on a cooling aggregate (Fischer Elektronik LAM 31005) in order to avoid overheating and to maximize LED lifespans. A small axial fan (ca. 0.15 W) on top of the aggregate additionally removes heat from the inside. Airflow is directed from the bottom to the top of the lamp, supporting air convection. Metal gauze at the bottom and the top of the lamp

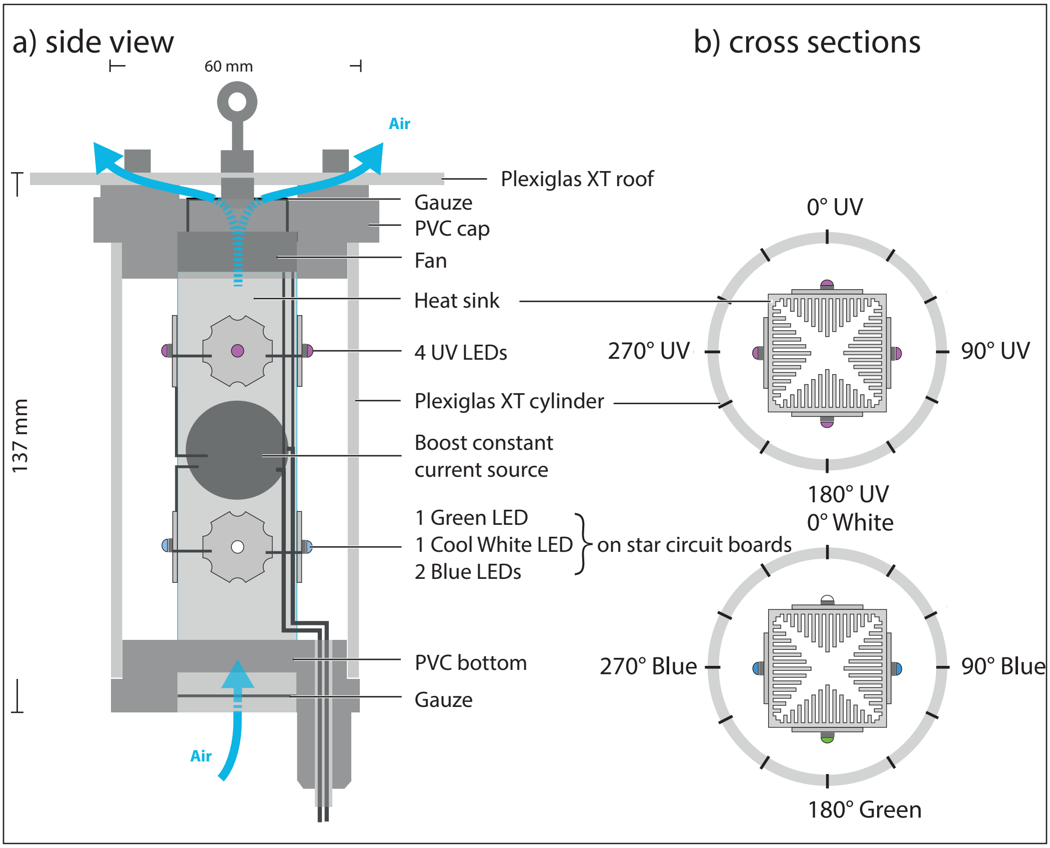

Figure 2. Design of the new LED lamp (scale 1:2). A total of 8 Power LEDs is arranged at two levels (4 UV, 2 blue, 1 green, 1 cool white).

prevents small insects and dirt from entering, and a transparent acrylic (Plexiglas® XT) roof protects the lamp from rain. The protective cylinder around the LEDs also consists of Plexiglas XT characterized by high transmission rates including for UV radiation (Fig. 1b). Alternatively, a matt Plexiglas cylinder can be used (Fig. 1b, Table 1). The bottom and top of the lamp are made of PVC. Inside is a cooling aggregate (heat sink) and outside a Plexiglas cylinder. In future models, PVC will be replaced by anodized aluminium. LEDs are connected in series to a Boost LED constant current source (pcb components Led Senser V2 Rev.2) that allows an input current in the given design of ca. 5–12 V DC. After performance tests with different currents, the output current was set to 350 mA.

Spectral measurements

The irradiance (E_e) of different lamps was measured in a dark room with a Specbos 1211 UV broadband spectro-radiometer aligned to the centre of the lamps at a distance of 50 cm (Fig. 3). Irradiance is defined as radiant flux (or intensity) received by a surface per unit area, here expressed as W $m^{-2}nm^{-1}$ and measured at wavelengths between 300 and 1000 nm. While irradiance refers to

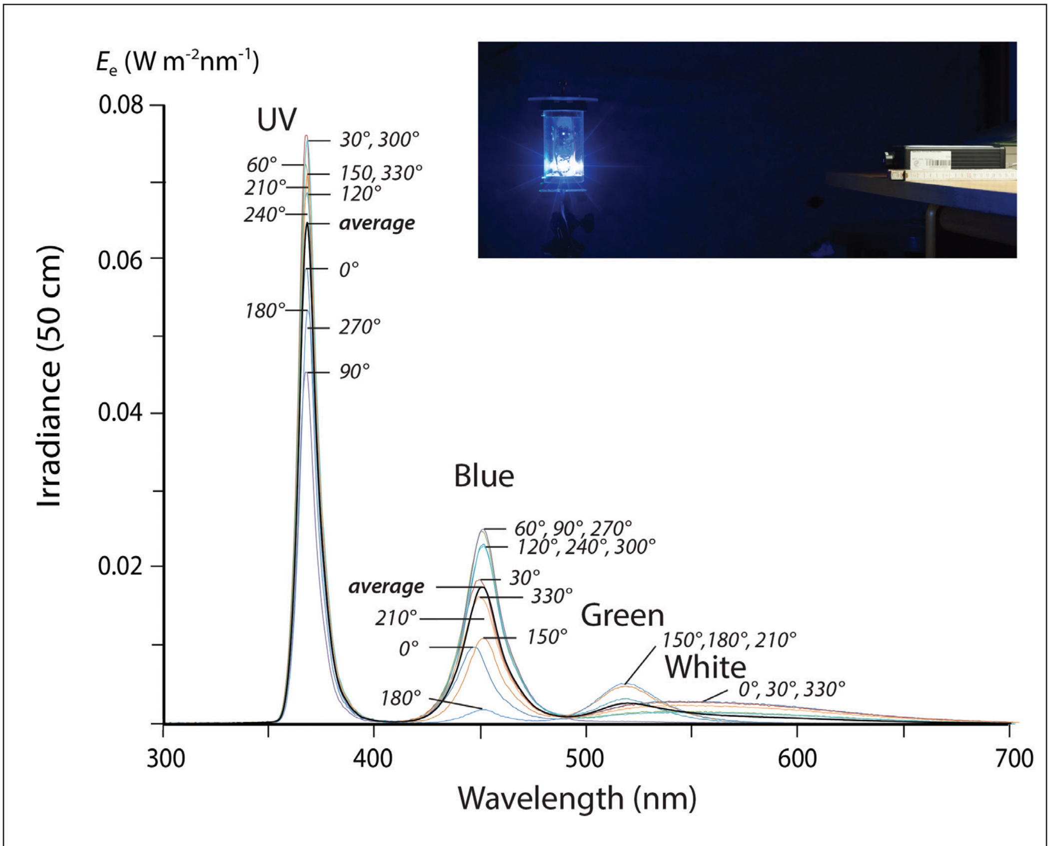

Figure 3. The irradiance of the new lamp was measured at a distance of 50 cm around its circumference at 12 points giving 30° between each. Average value: black line.

a receiving surface, the terms "radiance" and "emission" refer to the radiant source. Irradiance was calculated in total as well as separately for the spectral bands 300–400 nm, 401–650 nm, and 651–1000 nm. Because of the unequal emission patterns of the new LED lamp, irradiance was measured 12 times, at 30° angular intervals around the lamp, and the average was calculated for each wavelength (Fig. 3). Apart from the LED lamp, a number of lamps commonly used in light-trapping were also assessed (Table 1, Appendix 1). In cases where more than one lamp was measured, modest variation in the data was observed, as expected for standard industry products. For a comparison of UV irradiance of lamps and sunlight, irradiance from sunlight was measured on a sunny but hazy day on 17.iii.2016 at 10:50 in Jena, Germany (50.9° N). In addition, lamp and sunlight were filtered with regular clear glasses (Fielmann: Essilur, allyl diglycol carbonate (= CR 39) with additives, super-nonreflecting) and sun glasses (Fielmann: Rupp and Hubrach, allyl diglycol carbonate with additives, polarized, 85% grey).

The wattage of the lamps was measured with a Muker-J7 USB Multimeter QC2.0 QC3.0 and a REV Ritter 'energy cost measuring device' (Nr. 002580). The ratio between irradiance and watt-

Table 1. Irradiation of selected lamps and LEDs at wavelengths between 300 and 1000 nm, measured at a distance of 50 cm. A full list is provided in Appendix 1. *Italics*: Measurement of lamp within a gauze tower. Grey cells: wavelength band with highest irradiance. *Unlike other lamps in the test, the GemLight emits only into a single direction (max. 180°). ** Wattage and efficiency of the new LED lamp depend on the input voltage; Values are provided for 12 V and 5 V DC input, respectively.

Lamp	**300–400 nm**	**401–650 nm**	**651–1000 nm**	**300–1000 nm**	**Effective wattage (W)**	**Irradiation/ wattage (efficiency)**
Low pressure mercury vapour						
350 nm actinic tube in acrylic glass	0.44	0.04	0.01	**0.49**	8	0.06
in gauze tower	*0.25*	*0.10*	*0.01*	***0.36***	*8*	--
350 BLB in acrylic glass	0.14	0.01	0.01	**0.15**	8	0.02
in gauze tower	*0.08*	*0.02*	*0.01*	***0.11***	*8*	--
368 nm actinic tube in acrylic glass	0.45	0.04	0.01	**0.50**	8	0.06
in gauze tower	*0.26*	*0.12*	*0.01*	***0.39***	*8*	--
8 W BLB in acrylic glass	0.04	0.00	0.01	**0.05**	4	0.01
in gauze tower	*0.02*	*0.01*	*0.01*	***0.04***	*4*	--
Revoltec cold cathodes (twin sets)						
Cold cathode UV	0.32	0.01	0.00	**0.33**	3.9	0.09
Cold cathode blue	0.00	0.48	0.01	**0.49**	3.9	**0.13**
Cold cathode green	0.01	0.23	0.00	**0.24**	6.8	0.04
Tungsten filament lamps						
160 W mercury vapour	0.57	3.316	7.09	**10.98**	190	0.06
in gauze tower	*0.33*	*3.010*	*6.45*	***9.79***	*190*	--
200 W incandescent	0.04	1.54	8.36	**9.94**	180	0.06
LED lamps						
GemLight*	0.10	0.02	0.00	**0.13**	--	--
400 nm Infusino et al. (2017)	0.13	0.10	0.00	**0.23**	8	0.03
New LED lamp**						
(350 mA) in Plexiglas cylinder	0.77	0.64	0.01	**1.43**	10.4 / 13.4	**0.14 / 0.11**
without Plexiglas cylinder	*0.77*	*0.66*	*0.01*	***1.44***	10.4 / 13.4	**0.14 / 0.11**
with matt Plexiglas cylinder	*0.64*	*0.59*	*0.01*	***1.24***	10.4 / 13.4	**0.11** / 0.09
with sheet in background	*0.76*	*0.94*	*0.02*	***1.72***	10.4 / 13.4	--
in gauze tower	*0.34*	*0.71*	*0.01*	***1.06***	10.4 / 13.4	--

age at 50 cm between 300 and 1000 nm expresses the energy efficiency of the lamps. Temperature of LEDs was measured with an Omega hypodermic needle probe connected to an Omega HH21 thermometer.

Field work performance

A prototype, operated with an output current of 500 mA, was first tested in dry grassland near Leutra, Jena, Germany (29.vi.2016), and later in similar habitats in South Tyrol, Italy: Oberversant (2–13.vii.2016) and Innerunterstell (4.vii.2016). After the successful first field tests, a series of ten LED lamps, operated with an output current of 350 mA, became available in August 2016 and was used for a quantitative moth survey along a rain forest elevational gradient in the Cosñipata valley (Cusco province, Peru) for more than 50 sampling events (23.viii.–4.ix.2016, 12.8868° S, 71.4012° W–13.2003° S, 71.6172° W, 520–3500 m). Detailed analyses of this sampling campaign will be published in due course, but selected photographs illustrate the attraction of Lepidoptera to the lamp.

Results

Features of the new LED lamp

Pronounced irradiation peaks from the new LED lamp occur at 368 nm (UV), at 450 nm (blue), and at 520 nm (green) (Figs 1, 3–6). The mean irradiance of wavelengths between 300 and 1000 nm at a distance of 50 cm is 1.43 W m^{-2}. The irradiance without the protective Plexiglas cylinder is only minimally higher (1.44 W m^{-2}, Fig 1b), and the irradiance with a matt Plexiglas cylinder is ca. 13% lower (1.24 W m^{-2}, Fig. 1b). As expected, UV irradiation is relatively constant at all angles around the lamp, whereas more pronounced spatial peaks occurred with the blue, green, and white LEDs (Fig. 3). A white sheet in the background behind the lamp increases irradiance to 1.72 W m^{-2} (Fig. 4a). However, in this case irradiance is a theoretical value because a sheet can only be placed on one side of the lamp, and irradiance on the reverse of the sheet will be far lower. A gauze tower around the lamp led to a decrease of irradiance to 1.07 W m^{-2} (Fig. 4a), but in-depth comparisons are hindered by increased stray light–the whole gauze tower appears illuminated (Fig. 7). Remarkable in both cases is a partial shift from UV to blue irradiation. This can also be observed when measurements with and without a surrounding gauze tower are compared for a single UV LED (Fig. 4b).

When operated with a 12 V battery, the wattage of the lamp is ca. 10.4 W. When operated with a 5 V (powerbank) battery, the wattage is ca. 13.4 W. Without an axial fan, the LEDs reach (at room temperature) temperatures of between 43 and 53° C. With an operating fan, the temperature range is 30–33° C with a 12 V battery, and 33–39° C with a 5 V battery.

Comparison of lamps

Both the self-ballasted MV and the incandescent lamp assessed surpass by far the irradiance (full range 300–1000 nm) of the new LED lamp (Fig. 5a, Table 1). However, ca. two thirds of their respective irradiation is in the long wave spectrum (> 650 nm), much of it infrared. Remarkably, irradiation from the new LED lamp in the near-UV range between 300 and 400 nm is higher (Table 1)–despite having more than tenfold lower wattage. The MV lamp shows various narrow radiation peaks reflecting the characteristic spectral lines of mercury vapour and an increasing proportion of long wave radiation due to the tungsten filament. The incandescent lamp produces a continuously increasing long wave radiation spectrum but practically no UV radiation.

None of the other lamps that were compared surpass the irradiation from the new LED lamp, neither in total nor in a single wavelength band (Fig. 5b, Table 1, Appendix 1). All tested fluorescent low-pressure mercury tubes (BL / BLB) either show peaks around 350 or 368 nm (Fig. 5b). The highest total irradiation is from 368 nm and 350 nm actinic BL tubes (0.50 and 0.49 W $m^{-2}nm^{-1}$, respectively) whereas the 350 nm BLB tube shows a considerably lower irradiation (0.15 W $m^{-2}nm^{-1}$). All cold cathodes show clearly visible peaks in UV, blue, and green, with irradiance sums of 0.33, 0.49, and 0.24 W $m^{-2}nm^{-1}$, respectively.

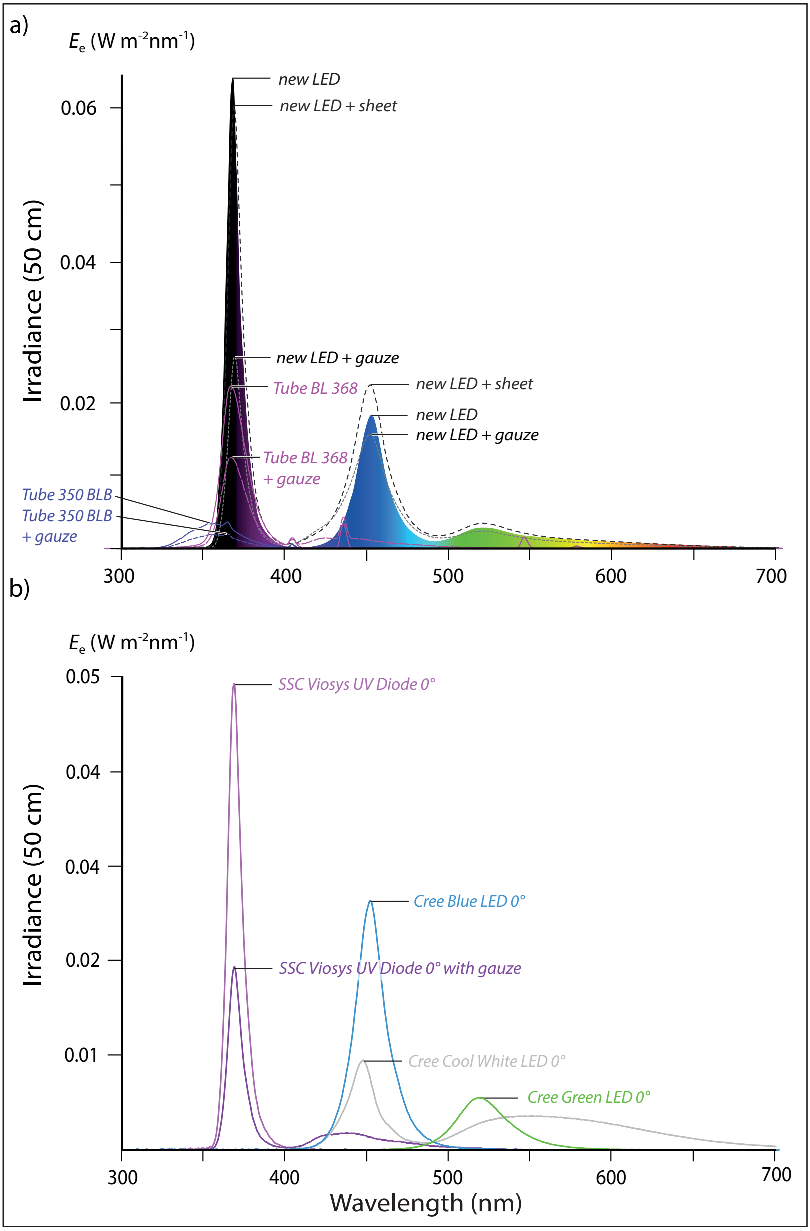

Figure 4. a. Irradiance from the four LED types used in the new LED lamp, measured at 50 cm distance and at 0° (see Fig. 3), and influence of Bioform 'light tower' gauze on the spectral composition of the UV LED. UV irradiance decreases significantly and a new blue peak appears at ca. 440 nm, probably due to optical brighteners applied to the textile. **b.** Influence of Bioform 'light tower' gauze and a white sheet on the irradiance of the new LED lamp, of a 368 nm fluorescent actinic BL tube and a 350 nm fluorescent BLB tube. In all cases, a part of the UV radiation is absorbed and re-emitted by the textile as blue light, caused by optical brighteners. Distance between measuring device and lamp: 50 cm. The tower gauze was placed between the measuring device and the lamp. The sheet was placed 15 cm behind the lamp (increased irradiation due to reflection).

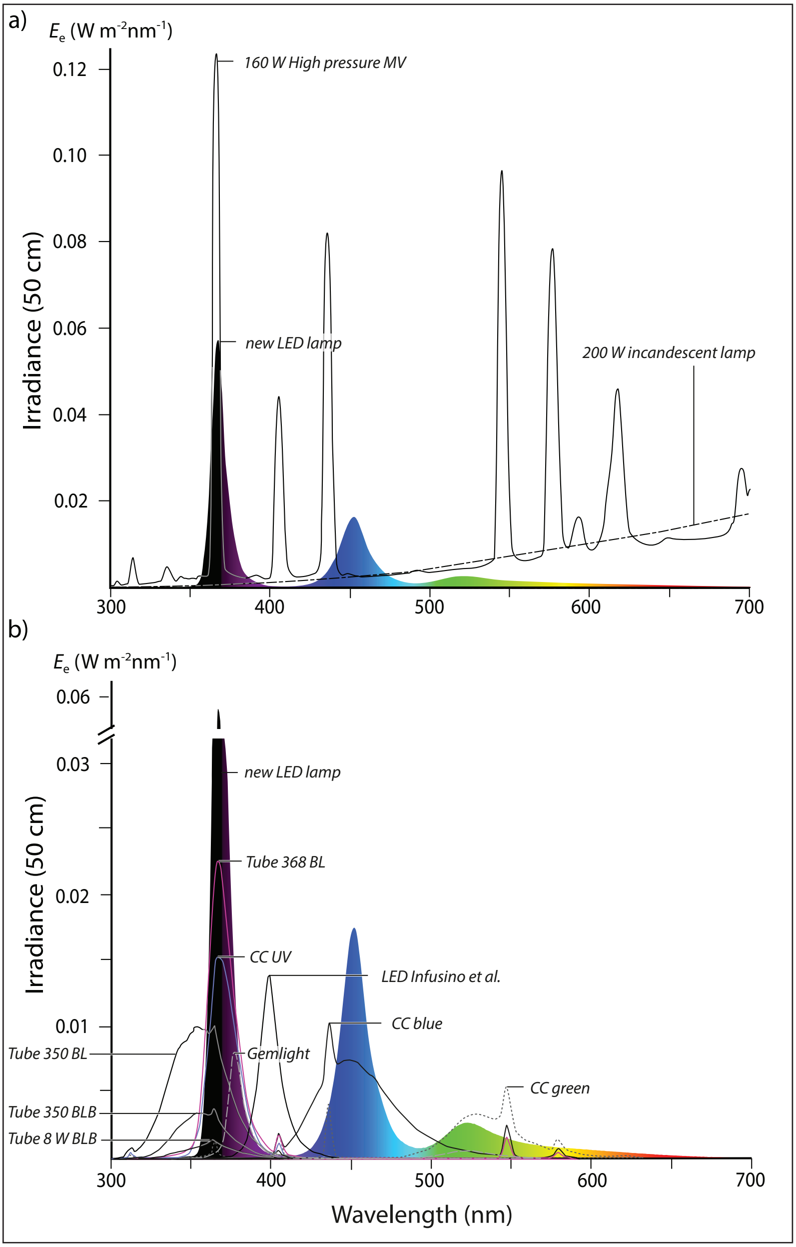

Figure 5. Irradiance from the new LED lamp (in colour), compared with other lamps. **a.** Compared with irradiation from a 190 W high-pressure mercury vapour (MV) bulb with tungsten filament (black line), and a 200 W incandescent lamp with tungsten filament (dashed black line). **b.** Irradiance from the new LED lamp (in colour), as compared to irradiance from various commonly used lamps used for insect collecting. CC blue: Blue cold cathode; CC green: Green cold cathode; CC UV: ultraviolet cold cathode; tube 350: low pressure actinic mercury vapour tube with 350 nm emission peak; tube 350 BL: low pressure mercury vapour blacklight tube with 350 nm emission peak; tube 368: low pressure mercury vapour tube with 368 nm emission peak. GemLight: GemLight UV LED at 0°. LED Infusino et al.: 400 nm LED stripe applied by Infusino et al. (2017).

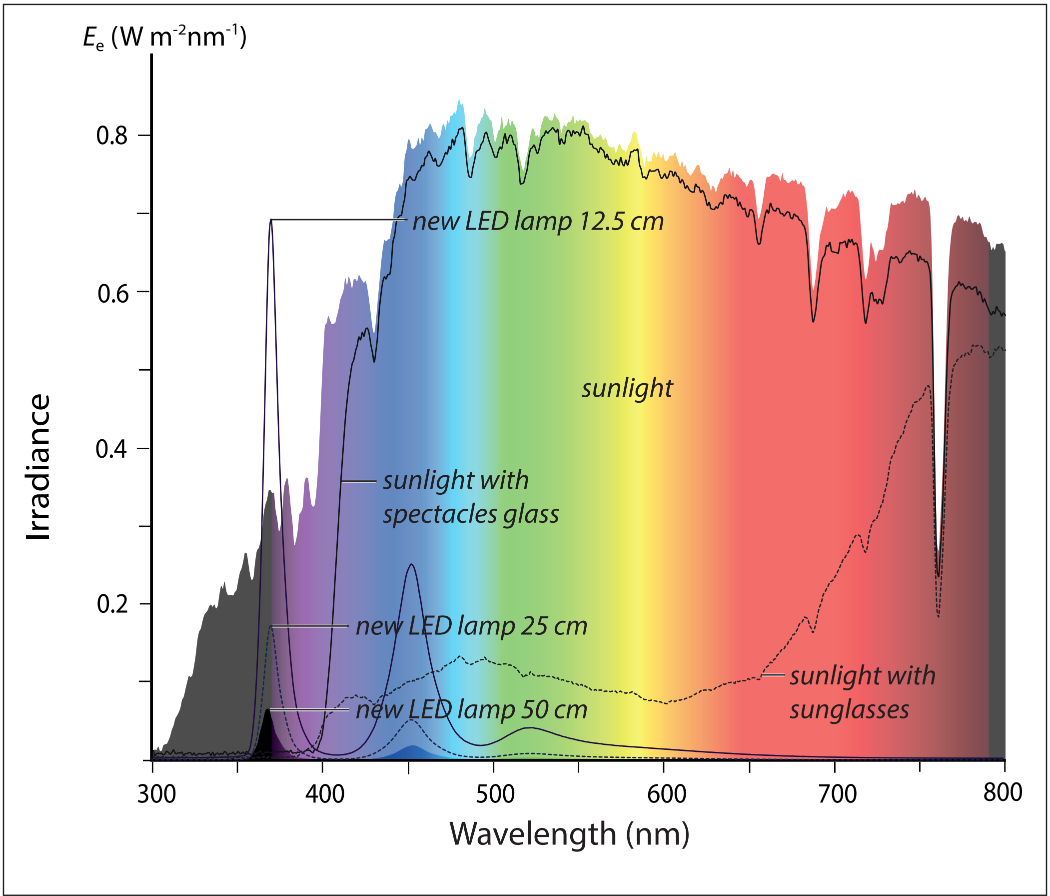

Figure 6. Irradiance from sunlight (in colour; 50.9° N, on a sunny, hazy day at 10:50h in March 2016), irradiance from sunlight with clear synthetic glasses (solid line), irradiance from sunlight with synthetic sunglasses (dashed line), and irradiance from the new LED lamp at distances of 50 cm (see all other Figs), 25 cm, and 12.5 cm. The two spectacle lens types almost completely absorb UV radiation.

Sunlight comparison and UV protection

Fig. 6 shows a comparison of the irradiance on a sunny March day in Jena with the irradiance of the new LED lamp at different distances from the measuring device. The UV irradiation from the new lamp at a distance of 50 cm (the same as in all standardized measurements) is small compared with the irradiance from the sun. However, irradiance from the LED lamp becomes higher at shorter distances. Normal spectacle glasses (allyl diglycol carbonate with additives) almost completely filter away UV radiation but allow almost full transmission of radiation > 400 nm. Sunglasses (allyl diglycol carbonate with additives) again filter UV radiation and also a large proportion of longer wavelengths.

First results from field work

Generally, the LED lamps attracted moths very well, including e.g. Geometridae, Noctuidae, Erebidae, Pyraloidea, Sphingidae, and many other taxa. Lamps were either mounted in front of a white

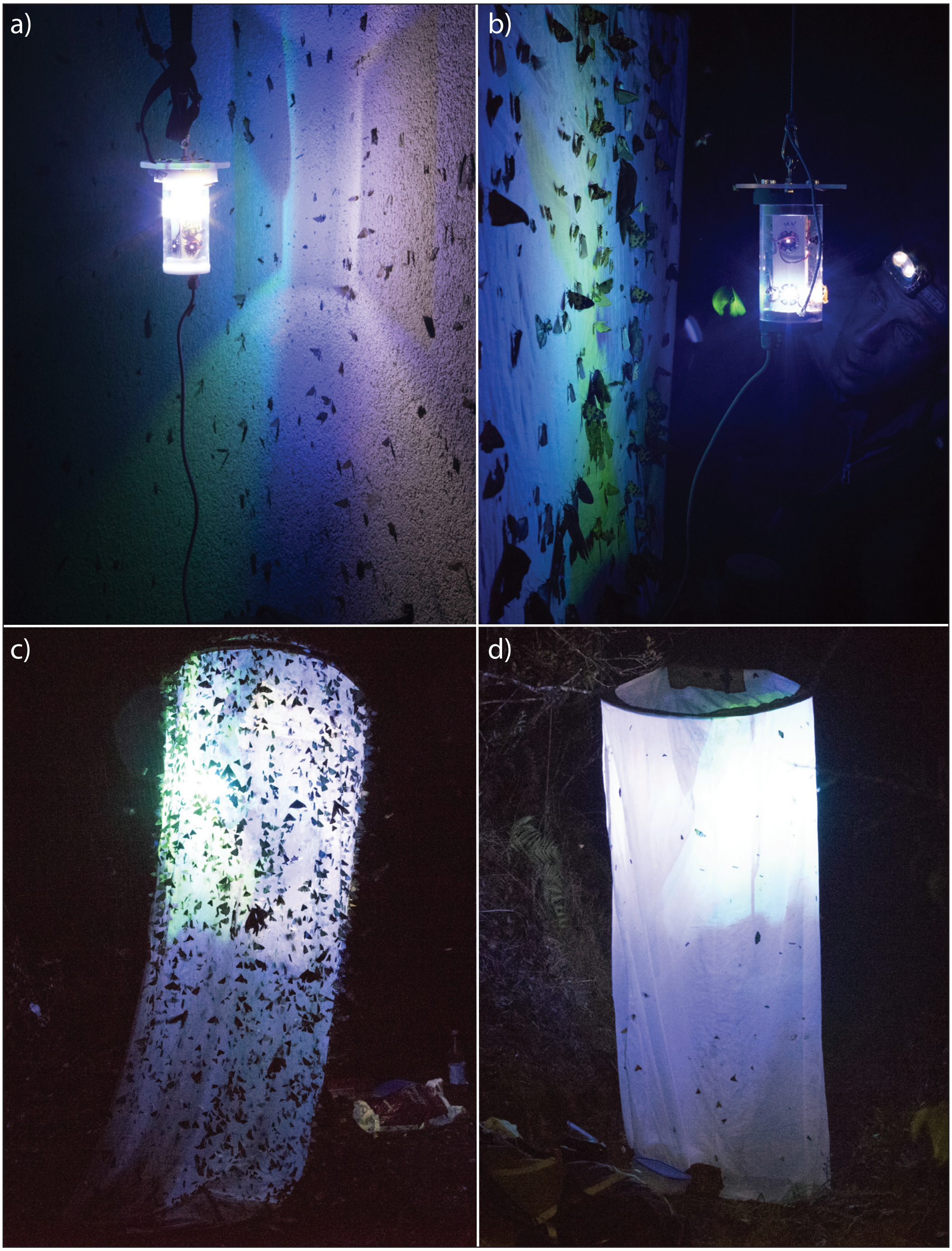

Figure 7. LED lamp used in field work. **a.** Lamp operating in front of a house wall, Oberversant, South Tyrol, Italy (8.vii.2016). **b.** Lamp operating in front of a white sheet, Paradise Lodge, Cosñipata valley, Cusco Province, Peru, 1360 m (30.viii.2016). **c.** Lamp operating in a gauze tower, Cosñipata valley, Peru, 1940 m (3.ix.2016). **d.** Lamp operating in a gauze tower, near Wayqecha station, Peru, 2890 m (4.ix.2016).

house wall in South Tyrol (Fig. 7a), in front of a white sheet in Peru (Fig. 7b) or in a gauze tower in Peru (Figs 7c,d). Most individual moths along the rain forest elevational gradient in Peru were collected at low and medium elevations. The "busiest" night in Peru occurred two days after new moon (3.ix.2016) at 1940 m (Figure 7c). Geometrid moths were the most abundant moth family at this elevation, and I estimate that at least 1000 individuals were attracted within less than three hours after dusk. Only one night later, far fewer specimens (ca. 100 individuals of Geometridae) were collected in a partly clear night at 2890 m (Fig. 7d).

Discussion

The new LED lamp was constructed with the aims of being lightweight, handy, robust, and energy efficient, and these aims were clearly fulfilled. First field tests have demonstrated that the lamp is very attractive to nocturnal Lepidoptera (Fig. 7), and a detailed analysis of the samples will be published in due course. The measurements carried out concentrate on irradiance rather than on total emission of the lamp, first because the required measuring device, a two-meter diameter Ulbricht sphere, was not available in Jena. Second, the chosen approach allowed comparison of irradiance from lamps in combination with gauze and sheets, as well as with incoming sunlight. Generally, comparisons between different lamps are never simple because lamps differ in their design, in their dimensions, and in the way radiation is emitted. All of these factors could possibly influence moth behaviour, and therefore measurement results should be regarded as an approximation of potential moth attractiveness, to be supplemented by field studies and physiological measurements.

The age and the cumulative operating hours of the lamps could have an impact on their performance, but it was beyond the scope of this paper to explore this effect in detail. For example, the emission of fluorescent tubes drops with age to ca. 80% in new-generation lamps (Sylvania BL 368 nm) and to ca. 50% in old-generation tubes (e.g. Sylvania BL 350 nm) (Havells-Sylvania 2012). Decreases are also expected to occur in LEDs, accelerated by high temperatures and high currents. For this reason, LEDs in the lamp are not being operated at the maximum possible current (700 mA) but only at 350 mA, aided by an efficient cooling system. Ageing of acrylic glass and other materials possibly also influences the radiation flux.

Clearly, a cross calibration study with other lamps is desirable. Such comparative studies have regularly shown that even lamps with fundamentally different light spectra attract similar moth assemblages. For example, Geometroidea samples attracted to an incandescent and a MV lamp were surprisingly similar (Intachat and Woiwod 1999; Infusino et al. 2017; Jonason et al. 2014). On the other hand, noctuid moths were more attracted to short wave radiation than geometrid moths (Somers-Yeates et al. 2014), so certain differences in samples obtained with different methods must be expected.

An unexpected result was the appearance of a blue peak at ca. 440 nm when 'light tower' gauze and a white sheet were used in combination with various lamps. In all cases, a part of the UV radiation is absorbed and re-emitted by the textile as blue light, caused by commonly used optical brighteners in textile production and in washing powders. This means that supposedly 'pure' UV sources such as BLB tubes and UV LEDs combined with a textile also emit a certain amount of blue light. This lowers energy efficiency to some extent, but the additional blue light possibly increases the attractiveness to insects.

The lamp itself has a weight of less than 500 g, and it can be operated for five to six hours with a standard powerbank, e.g. an Easy Acc battery (5 V, 26 Ah, 400 g). Since powerbank batteries are a mass product on the market used for mobile phones etc., their prices are reasonable, they can easily be transported in carry-on baggage and recharged with mobile solar panels in remote areas. The total equipment, including the lamp, powerbank and charging device (220 V AC to 5 V DC USB charger) weighs less than 1 kg. In comparison, any equipment operated with generators is far heavier because a generator alone weighs ca. 13 kg. Equipment operated with 12 V is usually connected to (heavy) lead batteries. For example, field work in Ecuador and Costa Rica (Brehm and Axmacher 2005; Brehm 2007) was undertaken with a 15 W actinic BL tube and a 15 W BLB tube, operated with a lead battery (12 V, 7 Ah, 2 kg). Together with the charging device, the equipment weighed ca. 4 kg. The size of the new LED lamp (6 x 14 cm) is also small, so that it easily fits into travel bags and backpacks. The lamp has furthermore proven to be robust in the field. In one case, the axial fan broke when a gauze tower was blown down in a thunderstorm. However, the lamp remained fully functional without the fan, but since a working fan reduces the temperature of the LEDs (by ca. 10° C), which leads to a longer lifetime of the diodes, it is recommended that a broken fan is replaced when it is practical to do so (it takes only a few minutes).

In terms of energy efficiency, the new LED lamp outperformed every other lamp that was tested (Table 1, Appendix 1), and total irradiance between 300 and 400 nm was greater than from any other tested lamp, even including strong, self-ballasted MV bulbs. If efficiency is to be maximized, the use of 12 V batteries is recommended but from a weight-optimising point of view, 5 V powerbank batteries are the better choice. The second most energy-efficient tested lamps are cold cathodes with an input voltage of 12 V (Table 1). Their use nonetheless requires heavier batteries or a step-up converter that lowers energy efficiency. Cold cathodes (especially blue ones) are very lightweight and appear to have the best price / performance ratio.

The new LED lamp emits the desired spectrum of different wavelengths (UV, blue, and green). Half of the LEDs are UV diodes because UV is particularly attractive to moths. However, the additional diodes are expected to contribute further to the attractiveness of the lamp, and to stimulate eye receptors sensitive to longer waves. When MV lamps are compared with BL and BLB tubes, MV lamps usually attract more moth species and individuals (e.g., Jonason et al. 2014; Tikoca et al. 2016). A possible reason is that MV lamps emit not only more UV radiation, but also a much broader spectrum, than fluorescent tubes. A major advantage of LEDs is that a light mix can experimentally be assembled from a wide range of available diodes (Cowan and Gries 2009; Kadlec et al. 2016). Future studies could assess whether a maximisation of UV radiation on the one hand versus a mixture of wavelengths on the other hand, results in a higher number of attracted moth species and individuals. The new LED lamp could easily be used for such experiments, and mixtures of different LEDs could be tested. In principle, the lamp could also be modified in such a way that more diodes, e.g. 12, 16, or 20, are mounted on an extended design.

Safety considerations

Ultraviolet radiation is well known for its harmful effects on skin and eyes, being linked to accelerated ageing, various forms of skin cancer, eye cataracts etc. (O'Sullivan and Tait 2014). Protection with appropriate glasses and sunscreen is therefore strongly recommended to all lepidopterists who often work in open sunlight. The potential hazard of light-trapping lamps used by entomologists has received little consideration to date. The data presented here suggest that UV irradiance at a distance

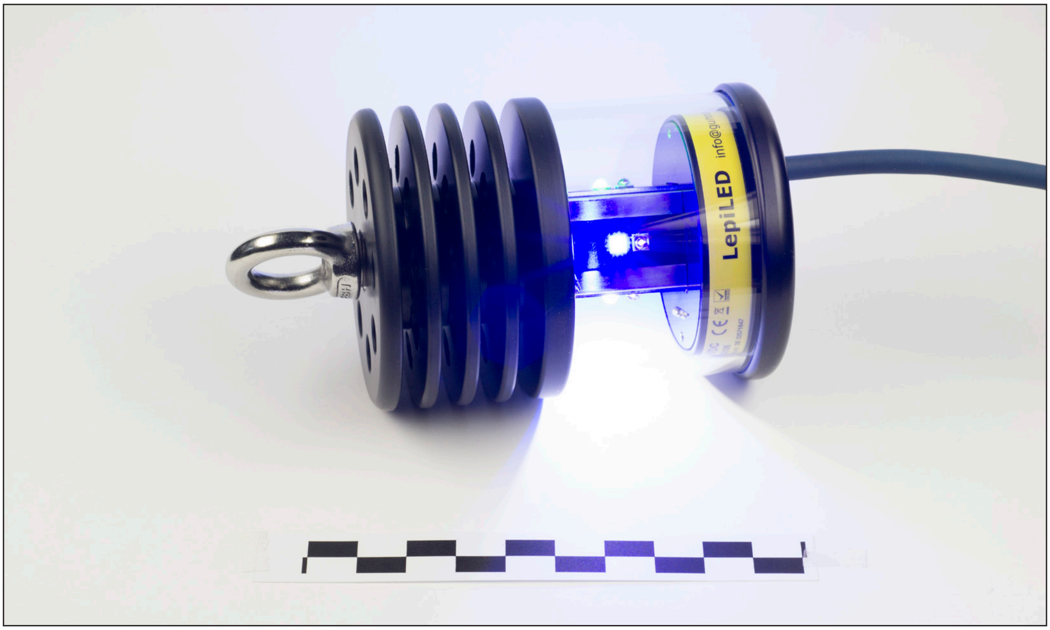

Figure 8. First exemplar of the commercially available lamp "LepiLED", height ca. 88 mm, diameter ca. 62 mm. Scale bar: 10 cm.

of 50 cm from the lamp is low compared with sunlight, which was relatively weak (51° N, low angle) compared to sunlight at lower latitudes, at higher angles, and at high elevations. This of course does not mean that UV lamps are generally harmless: irradiance strongly increases as distance decreases between lamp and exposed surface. As a general rule, it is certainly advisable to keep a reasonable distance from the lamp, depending on its type, and to avoid exposure of skin and eyes to the UV source at a short distance. High quality glasses (but not normal spectacle glasses) will often provide a sufficient protection, but UV transmission of glasses should individually be checked by an optician. In doubt, one can easily purchase safety-glasses which also protect from stray light. Good quality sun-glasses also protect from UV radiation, but only models with weak shading will be practicable for use at night.

Outlook

Further studies are required with regard to cross-calibration of the new LED lamp with existing lamps, including cold cathodes, which have been poorly studied so far. The lamp design is also open to experimental approaches in the field with different sets of LEDs. So far, only a small series of lamps has been available. However, a professionally manufactured model will be available for 395 € from the author (info@gunnarbrehm.de) in 2017. This model uses the same basic design as the lamp described in this paper. It weighs ca. 470 g, has a height of 88 mm and a diameter of 62 mm, the same input voltage (5–12 V) and a very similar set of LEDs (manufacturer: Nishia). Also, this model has almost identical emissions to the lamp described here. It is manufactured with anodized aluminium and borosilicate glass, and instead of a fan, it uses a passive cooling element and is totally waterproof. This model will hopefully make the LED technology available to a larger community of lepidopterists and other entomologists.

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Appendix 1

Table 2. Full list of tested lamps and LEDs with irradiance measured in different bands of wavelengths. Grey cells: LEDs used for the new LED lamp.

Type	Remarks / angle	Wattage effective (W)	Brand	Nr	300–400 nm	401–650 nm	651–1000 nm	300–1000 nm
Low pressure MV actinic tube (BL)	naked	8	Sylvania	Blacklight 368 F15W/T8/BL368	0.427	0.039	0.008	**0.474**
Low pressure MV actinic tube (BL)	naked in gauze tower	8	Sylvania	Blacklight 368 F15W/T8/BL368	0.256	0.090	0.007	**0.353**
Low pressure MV actinic tube (BL)	acrylic glass	8	Sylvania	Blacklight 368 F15W/T8/BL368	0.438	0.040	0.009	**0.487**
Low pressure MV actinic tube (BL)	acrylic glass in gauze tower	8	Sylvania	Blacklight 368 F15W/T8/BL368	0.251	0.098	0.008	**0.357**
Low pressure MV actinic tube (BL)	naked	8	Sylvania	Blacklight F15W/350 BL-T8	0.469	0.041	0.007	**0.517**
Low pressure MV actinic tube (BL)	naked in gauze tower	8	Sylvania	Blacklight F15W/350 BL-T8	0.264	0.126	0.008	**0.398**
Low pressure MV actinic tube (BL)	acrylic glass	8	Sylvania	Blacklight F15W/350 BL-T8	0.450	0.039	0.008	**0.497**
Low pressure MV actinic tube (BL)	acrylic glass in gauze tower	8	Sylvania	Blacklight F15W/350 BL-T8	0.256	0.124	0.008	**0.388**
Low pressure MV actinic tube (BL)	naked	9	Philips	PL-S 9W/12 Made in Poland	0.223	0.057	0.013	**0.293**
Low pressure MV actinic tube (BL)	naked in gauze tower	9	Philips	PL-S 9W/12 Made in Poland	0.109	0.063	0.012	**0.184**
Low pressure MV actinic tube (BL)	naked	13	Exo Terra	Repti Glo 5.0 UVB 13 W	0.053	0.492	0.054	**0.599**
Low pressure MV actinic tube (BL)	naked in gauze tower	13	Exo Terra	Repti Glo 5.0 UVB 13 W	0.029	0.482	0.053	**0.563**
Low pressure MV actinic tube (BL)	naked	12	Osram	Dulux S Blue UVA, 78 Color	0.441	0.075	0.022	**0.538**
Low pressure MV actinic tube (BL)	naked in gauze tower	12	Osram	Dulux S Blue UVA, 78 Color	0.247	0.137	0.016	**0.401**

Type	Remarks / angle	Wattage effective (W)	Brand	Nr	300–400 nm	401–650 nm	651–1000 nm	300–1000 nm
Low pressure MV actinic tube (BL)	naked	30	Kelly	Bug Killer 40W, ESL Lamp Nr. 71468	1.014	0.355	0.005	**1.374**
Low pressure MV actinic tube (BL)	naked in gauze tower	30	Kelly	Bug Killer 40W, ESL Lamp Nr. 71468	0.548	0.471	0.005	**1.024**
Low pressure MV blacklight-blue tube (BLB)	naked	8	No brand	F15 T8 BLB	0.144	0.005	0.013	**0.162**
Low pressure MV blacklight-blue tube (BLB)	naked in gauze tower	8	No brand	F15 T8 BLB	0.080	0.024	0.011	**0.115**
Low pressure MV blacklight-blue tube (BLB)	acrylic glass	8	No brand	F15 T8 BLB	0.135	0.005	0.010	**0.149**
Low pressure MV blacklight-blue tube (BLB)	acrylic glass in gauze tower	8	No brand	F15 T8 BLB	0.076	0.022	0.009	**0.106**
Low pressure MV blacklight-blue tube (BLB)	naked	8	No brand	F15 T8 BLB	0.141	0.004	0.007	**0.152**
Low pressure MV blacklight-blue tube (BLB)	naked in gauze tower	8	No brand	F15 T8 BLB	0.080	0.021	0.007	**0.108**
Low pressure MV blacklight-blue tube (BLB)	acrylic glass	8	No brand	F15 T8 BLB	0.129	0.003	0.006	**0.138**
Low pressure MV blacklight-blue tube (BLB)	acrylic glass in gauze tower	8	No brand	F15 T8 BLB	0.070	0.021	0.007	**0.098**
Low pressure MV blacklight-blue tube (BLB)	naked	19	Omnilux	Energy Saving Lamp 3U 20W E27	0.184	0.009	0.004	**0.197**
Low pressure MV blacklight-blue tube (BLB)	naked in gauze tower	19	Omnilux	Energy Saving Lamp 3U 20W E27	0.105	0.034	0.003	**0.142**
Low pressure MV blacklight-blue tube (BLB)	naked	4	no brand		0.041	0.002	0.008	**0.051**
Low pressure MV blacklight-blue tube (BLB)	naked in gauze tower	4	no brand		0.021	0.008	0.006	**0.035**
Cold cathode (twin set)	naked	3,9	Revoltec	UV RM130	0.324	0.009	0.001	**0.334**
Cold cathode (twin set)	naked	3,9	Revoltec	Blue RM128	0.004	0.483	0.005	**0.492**
Cold cathode (twin set)	naked	6,8	Revoltec	Green RM125	0.007	0.231	0.003	**0.241**

Type	Remarks / angle	Wattage effective (W)	Brand	Nr	300–400 nm	401–650 nm	651–1000 nm	300–1000 nm
High pressure MV lamp, self-ballasted	naked	190	Osram	HVL 160 W	0.567	3.316	7.093	**10.975**
High pressure MV lamp, self-ballasted	naked in gauze tower	190	Osram	HVL 160 W	0.331	3.010	6.454	**9.794**
High pressure MV lamp, self-ballasted	naked	190	Osram		0.694	3.132	6.330	**10.156**
High pressure MV lamp, self-ballasted	naked in gauze tower	190	Osram		0.348	2.443	4.879	**7.671**
High pressure MV BLB lamp, self-ballasted	naked	190	Omnilux	UV Lampe 160 W / E27	0.306	0.048	1.475	**1.829**
High pressure MV BLB lamp, self-ballasted	naked in gauze tower	190	Omnilux	UV Lampe 160 W / E27	0.211	0.113	1.466	**1.789**
Incandescent lamp	naked	180	no brand	200 W (E27)	0.035	1.541	8.364	**9.940**
LED UV + Green	naked	nA	Worldwide Butterflies	GemLight	0.104	0.024	0.000	**0.129**
LED UV + Green	naked in gauze tower	nA	Worldwide Butterflies	GemLight	0.055	0.035	0.000	**0.090**
LED UV	naked	8	no brand		0.129	0.104	0.000	**0.234**
LED UV	naked in gauze tower	8	no brand		0.069	0.108	0.000	**0.178**
LED UV	0°	at 350 mA	SSC Viosys	UV CUN66A1B	0.610	0.005	0.000	**0.615**
LED UV	0° gauze I	at 350 mA	SSC Viosys	UV CUN66A1B	0.274	0.099	0.000	**0.373**
LED UV	0° gauze II	at 350 mA	SSC Viosys	UV CUN66A1B	0.275	0.100	0.001	**0.375**
LED UV	30°	at 350 mA	SSC Viosys	UV CUN66A1B	0.526	0.011	0.002	**0.539**
LED UV	60°	at 350 mA	SSC Viosys	UV CUN66A1B	0.397	0.009	0.002	**0.408**
LED UV	0°	at 350 mA	Nishia	NCSU033B	0.446	0.004	0.000	**0.450**
LED UV	30°	at 350 mA	Nishia	NCSU033B	0.452	0.003	0.001	**0.456**
LED UV	60°	at 350 mA	Nishia	NCSU033B	0.218	0.002	0.000	**0.220**

Type	Remarks / angle	Wattage effective (W)	Brand	Nr	300–400 nm	401–650 nm	651–1000 nm	300–1000 nm
LED UV	90°	at 350 mA	Nishia	NCSU033B	0.000	0.000	0.000	**0.000**
LED UV	0° in gauze tower	at 350 mA	Nishia	NCSU033B	0.189	0.047	0.000	**0.236**
LED UV	0°	at 350 mA	Winger	WEPUV3-S2 Blacklight	0.137	0.252	0.001	**0.391**
LED UV	0° gauze I	at 350 mA	Winger	WEPUV3-S2 Blacklight	0.062	0.203	0.001	**0.266**
LED UV	0° gauze II	at 350 mA	Winger	WEPUV3-S2 Blacklight	0.064	0.213	0.001	**0.278**
LED UV	30°	at 350 mA	Winger	WEPUV3-S2 Blacklight	0.109	0.247	0.001	**0.357**
LED UV	60°	at 350 mA	Winger	WEPUV3-S2 Blacklight	0.096	0.225	0.001	**0.322**
LED UV	0°	at 350 mA	no brand		0.188	0.010	0.000	**0.199**
LED UV	30°	at 350 mA	no brand		0.160	0.009	0.000	**0.169**
LED UV	60°	at 350 mA	no brand		0.093	0.006	0.000	**0.100**
LED UV	90°	at 350 mA	no brand		0.002	0.000	0.000	**0.003**
LED Turquoise	0°	at 350 mA	Bridgelux	Turquoise	0.000	0.237	0.000	**0.238**
LED Turquoise	30°	at 350 mA	Bridgelux	Turquoise	0.001	0.214	0.000	**0.215**
LED Turquoise	60°	at 350 mA	Bridgelux	Turquoise	0.000	0.249	0.000	**0.250**
LED Turquoise	90°	at 350 mA	Bridgelux	Turquoise	0.000	0.029	0.000	**0.029**
LED Blue	0°	at 350 mA	Cree	XP-E2 Royal Blue	0.003	0.665	0.002	**0.670**
LED Blue	30°	at 350 mA	Cree	XP-E2 Royal Blue	0.002	0.555	0.003	**0.560**
LED Blue	60°	at 350 mA	Cree	XP-E2 Royal Blue	0.001	0.447	0.002	**0.451**
LED Blue	0°	at 350 mA	Bridgelux	Royal Blue	0.003	0.502	0.002	**0.507**
LED Blue	30°	at 350 mA	Bridgelux	Royal Blue	0.004	0.611	0.002	**0.617**
LED Blue	60°	at 350 mA	Bridgelux	Royal Blue	0.003	0.556	0.002	**0.560**
LED Blue	90°	at 350 mA	Bridgelux	Royal Blue	0.000	0.099	0.001	**0.101**
LED Blue	0° in gauze tower	at 350 mA	Bridgelux	Royal Blue	0.002	0.404	0.000	**0.407**
LED Blue	0°	at 350 mA	Winger	WEPRB3-S1 Royal Blue	0.002	0.483	0.002	**0.487**
LED Blue	0° gauze I	at 350 mA	Winger	WEPRB3-S1 Royal Blue	0.002	0.366	0.002	**0.371**
LED Blue	0° gauze II	at 350 mA	Winger	WEPRB3-S1 Royal Blue	0.001	0.364	0.003	**0.368**
LED Blue	30°	at 350 mA	Winger	WEPRB3-S1 Royal Blue	0.002	0.408	0.001	**0.411**

Type	Remarks / angle	Wattage effective (W)	Brand	Nr	300–400 nm	401–650 nm	651–1000 nm	300–1000 nm
LED Blue	60°	at 350 mA	Winger	WEPRB3-S1 Royal Blue	0.000	0.013	0.001	**0.014**
LED Green	0°	at 350 mA	Cree	XP-E2 Green	0.000	0.228	0.003	**0.231**
LED Green	30°	at 350 mA	Cree	XP-E2 Green	0.000	0.222	0.002	**0.225**
LED Green	60°	at 350 mA	Cree	XP-E2 Green	0.000	0.166	0.002	**0.169**
LED Green	0°	at 350 mA	Bridgelux	Emerald Green	0.000	0.213	0.001	**0.214**
LED Green	30°	at 350 mA	Bridgelux	Emerald Green	0.000	0.216	0.001	**0.217**
LED Green	60°	at 350 mA	Bridgelux	Emerald Green	0.000	0.202	0.000	**0.202**
LED Green	90°	at 350 mA	Bridgelux	Emerald Green	0.000	0.030	0.000	**0.031**
LED Green	0° in gauze tower	at 350 mA	Bridgelux	Emerald Green	0.000	0.230	0.001	**0.231**
LED Green	0°	at 350 mA	Winger	WEPGN3-S1 Green	0.000	0.236	0.001	**0.237**
LED Green	0° gauze I	at 350 mA	Winger	WEPGN3-S1 Green	0.000	0.167	0.001	**0.167**
LED Green	0° gauze II	at 350 mA	Winger	WEPGN3-S1 Green	0.000	0.168	0.001	**0.169**
LED Green	30°	at 350 mA	Winger	WEPGN3-S1 Green	0.000	0.236	0.000	**0.237**
LED Green	60°	at 350 mA	Winger	WEPGN3-S1 Green	0.000	0.213	0.000	**0.214**
LED Cool White	0°	at 350 mA	Cree	XP-L V6 Cool White	0.001	0.647	0.051	**0.699**
LED Cool White	0° gauze I	at 350 mA	Cree	XP-L V6 Cool White	0.001	0.417	0.036	**0.453**
LED Cool White	30°	at 350 mA	Cree	XP-L V6 Cool White	0.001	0.532	0.045	**0.578**
LED Cool White	60°	at 350 mA	Cree	XP-L V6 Cool White	0.001	0.359	0.034	**0.394**
LED Cool White	0°	at 350 mA	Bridgelux	Cool White	0.001	0.482	0.034	**0.518**
LED Cool White	30°	at 350 mA	Bridgelux	Cool White	0.001	0.399	0.030	**0.429**
LED Cool White	60°	at 350 mA	Bridgelux	Cool White	0.000	0.312	0.025	**0.338**
LED Cool White	90°	at 350 mA	Bridgelux	Cool White	0.000	0.014	0.001	**0.015**
LED Cool White	0° in gauze tower	at 350 mA	Bridgelux	Cool White	0.001	0.348	0.027	**0.375**
LED Cool White	0°	at 350 mA	Winger	WEPCW3-S1 Cool White	0.001	0.314	0.015	**0.331**
LED Cool White	0° gauze I	at 350 mA	Winger	WEPCW3-S1 Cool White	0.000	0.225	0.012	**0.237**
LED Cool White	0° gauze II	at 350 mA	Winger	WEPCW3-S1 Cool White	0.001	0.237	0.012	**0.250**
LED Cool White	30°	at 350 mA	Winger	WEPCW3-S1 Cool White	0.001	0.274	0.014	**0.289**
LED Cool White	60°	at 350 mA	Winger	WEPCW3-S1 Cool White	0.001	0.182	0.010	**0.193**