Light in standardised insect photography and description of lighting devices, including the UV range

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Abstract. Digital photography has become indispensable in many areas of biology and plays an essential role in digitization in museums and for the analysis of traits of organisms. The aspect of lighting quality has received surprisingly little attention so far, although good colour rendering is an important criterion. This paper provides an overview of the light quality of various lighting systems in three natural history museums. Light quality is usually expressed by the Colour Rendering index. Here, the relatively strict CIE (International Commission on Illumination) R_e index, based on the matching of 16 colours, is used. It presents three self-developed lighting devices with different designs: a light cylinder (also suitable for UV photography of individual objects), a light box for photographing entire insect boxes and a light hemisphere for photographing specimens with reflective surfaces. No light source measured in the natural history museums in London and Berlin achieves an R_e index value of >90. Compared to daylight (R_e index 98–99), modern daylight LEDs perform best in the new equipment presented (R_e 97–98). Existing LED lighting systems sometimes have very pronounced blue peaks and inequalities in the spectrum. The R_e values are in the range between 45 and 82. Xenon light sources (such as flash units) show a balanced spectrum (R_e index 87). Devices with fluorescent tubes (mercury vapour) achieve R_e values of 65 to 84. The new devices ensure shadow-free and homogeneous illumination (deviation of the measured irradiance in the area < 5%) and the respective objectives (suitability for photography in the UV range, photography of entire boxes, low-reflection photography) are achieved. The paper shows some astonishing deficits in light quality in the photography and digitization of insects, which very probably also apply to other areas in biology and beyond. Digitization programs should always check the quality of their lighting and incorporate better light sources if necessary. LEDs with daylight quality are readily available and represent a high-quality alternative. Capturing colour patterns in the UV range enables the documentation of a biologically essential component of the electromagnetic spectrum. It should therefore play a far greater role in digitization programs as well as in ecological analyses.

Introduction

Digital photography plays an outstanding role in many areas of biology in general and entomology in particular. For example, it is indispensable in the description of species and in morphology, but it also plays an essential role in the digitization of collections in museums (Häuser et al. 2005), large-scale collection campaigns (Steinke et al. 2024) and for ecological analyses and quantitative

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methods such as the determination of traits (Mungee and Athreya 2020). However, the exact methods used are often barely documented in publications (usually with the exception of the camera model and lens used). Professional photography opens up a myriad of (setting) options, but this can present inexperienced users with difficult decisions. This article is therefore intended to provide assistance in the area of standardized studio photography. This cannot be done with natural light because it changes during the day and is not always available. The right choice of light source is therefore important, as otherwise the image quality will be impaired. This is not only an aesthetic problem, but can also lead to distorted colour impressions and incorrect measurements. The Federal Agencies Digital Guidelines Initiative (2023) generally recommends a Colour Rendering Index (CRI) of more than 90 as appropriate for cultural heritage imaging. It can reach a maximum of 100 (daylight or incandescent light). CRI should properly be called the CIE (International Commission on Illumination) R_a or R_e value (see Methods).

In this article, some common and widely used light sources that play an important role in the photography and digitization of insects are spectrally measured. These, in particular, include mercury vapour fluorescent tubes, which are used in reproduction systems and light boxes. In recent years, LED lamps have become increasingly established in many areas, although they vary considerably in terms of energy efficiency and light quality. Commercially available flash units also continue to play an important role in macro photography, as they are considered to be true to colour (Morris 2005). The measurements carried out here are to be understood as examples – no larger selection of microscopes was measured – the focus of the work here is on the macroscopic range.

Subsequently, three lighting devices that I have developed and tested in recent years are presented. These are (1) a light cylinder for photographing individual moths and other insects (upper- and underside) in the VIS (visible) and UV range, (2) a light box in which complete insect drawers can be photographed and (3) a light hemisphere, which was developed primarily for low-reflection photography of liquid surfaces (with insect samples). In addition, some recommendations on camera equipment and settings are given (Box 1) and various materials are tested as backgrounds. The focus of the article is on good lighting. Aspects such as stacking photography are not covered and there is no evaluation of cameras or macro lenses, as this would go beyond the scope of this paper. The aim is to provide an up-to-date overview of the light quality of various lighting systems and to evaluate them, as well as to present the results that can be achieved with the three lighting devices described. These should be able to take photographs of insects efficiently, with very good light quality, shadow-free (Eckweiler 2001) and under conditions that are as homogeneous as possible (Ariño and Galicia 2005).

Material and methods

Abbreviations

CIE	International Commission on Illumination
CRI	Colour Rendering Index
LED	Light emitting diode
NHMUK	Natural History Museum, London, UK
RGB	Red, Green, Blue colour space
UV	Ultraviolet
VIS	visible (for humans)

Spectral measurements

For this paper, spectral measurements were carried out and documented using a Blue Spec Cube spectroradiometer from JETI (Jena, Germany). This was done in a similar way to that described by Brehm (2017). The focus is on the measurement of light sources for the photography and digitization of insects (and other objects) in natural history museums. Measurements were carried out between 2019 and 2024 in Jena, Berlin and London. For a better understanding and classification of the results, other light sources used in the museums (workrooms, exhibitions) were also measured, as good light seems desirable in all working areas of a museum. The widespread 'Colour Rendering Index' (CRI) is used to assess the quality of light. It reaches its maximum of 100 or just below in daylight and daylight-like sources. The CRI index is based on the agreement in the representation of eight or 16 standard colours, correctly referred to as CIE R_a index and CIE R_e index, respectively. I focus on the stricter index with the higher quality standard (i.e. the CIE R_e index with 16 standard colours).

Quantitative measurements were also carried out in all three devices to check the uniformity of the lighting. Uniformity of illumination is of obvious importance; in cinema projectors, for example, the ST 431-1:2006 standard stipulates that the peripheral areas must have at least 75% of the brightness of the centre. If images are to be evaluated quantitatively, all image areas should be evenly illuminated in order to prevent measurement artifacts. For the evaluation, one measurement was taken in the centre and four measurements in the respective corners. A total of nine measurements were carried out in the light hemisphere due to the increase in brightness observed at the edges. Suppl. material 1 shows the measurement points and the measurement results in detail.

Photographic equipment including UV photography

Various full-frame mirrorless cameras from Sony are used for photography, but products of similar quality can also be used for the applications described. For photographing individual insects, I use a Sony Alpha 7 camera (24.3 megapixels), which was modified according to the specifications of Prutchi (2017), i.e. the visible pass/IR cut filter directly in front of the sensor was removed by a specialist company. The lens used is an EL Nikkor 80 mm f/5.6 (quartz glass). As this lens cannot be focused by itself, a bellows device is used as an intermediary. The bellows (dating from the 1970s, made by Leitz, Wetzlar) is marked with different levels of magnification. Photographs are taken at the following scales: 1:1, 1:1.25, 1;1.5, 1:1.75, 1:2, 1:2.5 and 1 to 2.74 (maximum range). For even larger moths, the bellows is replaced by an intermediate ring (Leica R Macro Adapter). With this an image scale of 1:4.74 is achieved. Suppl. material 1 provides an overview of the image scales and the light measurements at each stage in graphic form. The distance between the filter wheel (see below) and the object ranges between 9.4 cm (scale 1:1) and 41.0 cm (scale 1:4.74) (details in Table 2). A filter wheel was mounted in front of the lens using an adapter, which can be operated using an electronic control (Lab View) with a Windows tablet. For normal images (VIS range), a visible pass/IR cut filter is again used, which only allows radiation in the range between 400 and 780 nm to pass through. For UV photography, on the other hand, a Baader U filter is used (Prutchi 2017), which only allows UV radiation in the range between approx. 320–400 nm to pass through. The sensitivity of the camera sensor was measured with a monochromator (Optronic Laboratories OL750/421S). This was done in steps of 2 nm in the ranges between 325–399 nm (UV range with a deuterium lamp) and between 400–800 nm (VIS range with a halogen lamp). In the resulting photographs, the sum of the brightness of all pixels in the image was determined. This was done for all

three colour channels in the VIS range and only for the red channel in the UV range – as this is by far the most sensitive colour channel. I use a Sony alpha 7R mark IV camera (61.0 megapixels) in combination with a 60 mm Leica Macro Elmarit f/2.8 to photograph whole insect drawers. For boxes lying inside the drawers (size a quarter of the drawer) I use a 100 mm Leica Apo Macro Elmarit f/2.8. Both high-class lenses have a manual focus and were manufactured in the 1980s.

Box 1. Recommendations for photographic equipment and camera settings.

The most suitable camera settings vary depending on the objects and also the purpose for which the images are to be used. However, there are many aspects that are similar for the vast majority of applications. When choosing a camera, it is important to consider whether the results are primarily to be produced quickly and inexpensively, or whether the focus is on high-quality results and long-term applications or archiving. For high-quality images, good quality SLR cameras, but above all mirrorless cameras and potentially also industrial cameras, should be considered. When it comes to lenses, the choice falls on macro lenses with very good optical properties, i.e. with low vignetting, low distortion and low chromatic aberration. The choice of focal length depends on the desired working distance. When photographing whole drawers, the distance to the sensor is already 124 cm with a focal length of f = 60, so that a longer focal length is not practical. In the field of studio photography and non-moving objects, shutter speed does not play a decisive role, and old manual lenses can also be used, as these can usually be connected well to mirrorless cameras using adapters and often have excellent optical properties.

Modern cameras offer a wide range of setting options, of which only the most important can be mentioned here. I always work in manual mode, where the aperture and shutter speed are set manually. The best resolution is achieved with an open aperture, the greatest depth of field with a closed aperture. In stacking photography, an almost open aperture is normally used. If a prepared moth or butterfly (which tends to be a "two-dimensional" object) is photographed instead of a truly three-dimensional object (such as a beetle), a single shot is sufficient for many purposes to achieve good results. In this case, a medium aperture should be selected so that a sufficient depth of field is guaranteed without compromising the absolute resolution too much. For the devices presented, an aperture of f/16 was selected in the photo cylinder, an aperture of f/5.6–8 when photographing insect boxes at a great distance and an aperture of f/11 when photographing ethanol samples. The correct exposure time results from the selected sensitivity (ISO setting) and aperture setting. ISO values with the lowest noise are recommended, i.e. low values of 100 or below. In order to fully standardize the exposure, it is necessary to use a standardized grey card or reflectance standards (Troscianko and Stevens 2015). The final exposure is only achieved by processing the raw image so that the result is completely uniformly exposed and comparable. I recommend taking photographs in raw format. The images can be edited and exported in appropriate programs such as CameraRaw or Lightroom (Adobe). Tif-files have proven to be a reliable lossless archive format (Crick 2005), but jpg-files can also be exported for many applications. The raw files should always be archived and given clearly comprehensible file names. As the exposure time can be relatively long depending on the light source, vibrations during the exposure must be avoided. This can be achieved using a remote shutter release, control via software on a laptop/PC or a delayed shutter release. When adjusting the white balance, the user should pay attention to the colour temperature of the light source (see Table 1). For light sources similar to daylight, the light temperature should be set to 5500 K, for example. However, the final white balance is achieved by processing the raw format ("pipette tool" on the standard), so that any colour cast can be subsequently removed.

A scale should be shown in each image. Overall, it is recommended to use a scale that is as uniform as possible – 10 mm is generally recommended for lepidopterans. The position of the scale in the image should also always be the same. Both of these factors facilitate subsequent automated evaluation by algorithms. The chessboard-like scale shown in Fig. 1e, f, for example, can be recognized very well automatically. Although it is technically possible to subsequently insert a scale into the image, this is only an option for applications in which the settings are constant. If the image ratio changes frequently, a scale should always be available to avoid confusion. I use a scale that is equipped with two reflectance standards (Troscianko and Stevens 2015), in my case a 95% standard and a 10% standard. It is not necessary to always map complete standardized colour scales (especially when space is limited). Rather, reliable measurements of light quality should be made and documented once for a given setup. It is more effective in the long term to optimize the light quality than documenting a possibly poor light quality on every shot.

In many digitization programs, e.g. at the Natural History Museum in London (NHMUK), labels are recorded together with the insect. This has the advantage that there is no confusion and the insect and label are always clearly assigned. The disadvantage, however, is that the process tends to be time-consuming, as all the individual parts have to be arranged so that they lie in one focal plane. I therefore work with separate images of object and label in the case of non-standardized labelled animals. For insects that are recorded in modern and standardized campaigns, recording the label is obsolete because all location data is already recorded in a database and time and storage costs can be saved without loss.

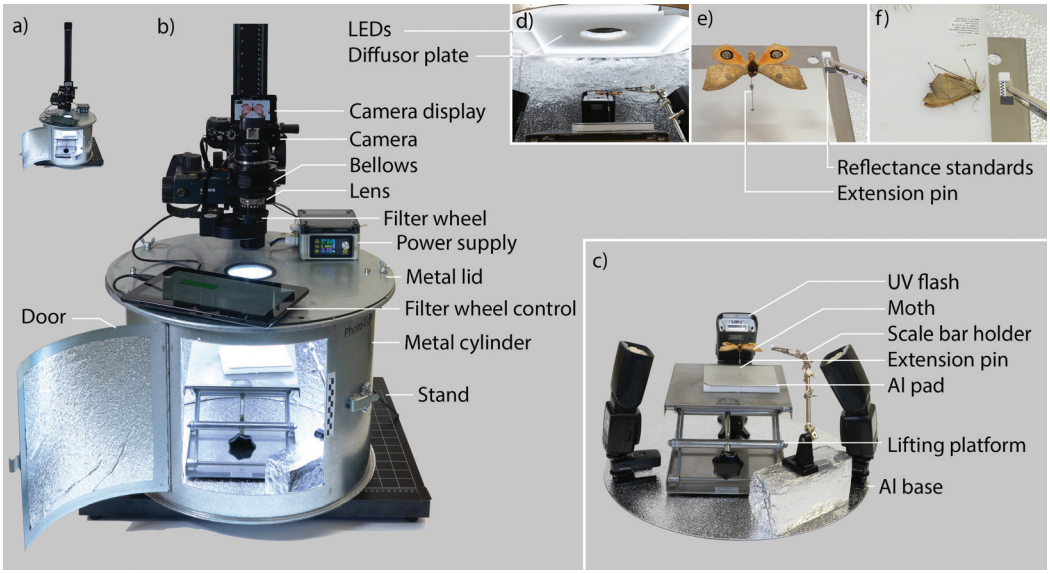

Figure 1. Light cylinder for VIS and UV photography: **a.** Reduced overview; **b.** Overview with open door (Scale: 10 cm); **c.** Structure of the lifting platform and three UV flash units in the cylinder. **d.** Interior view of the lighting on the ceiling; **e.** Moth with scale; **f.** Moth underside during photography of the proboscis length (or photography of labels) on polyethylene plate.

Light cylinder for VIS und UV photography

Moths and other insects are photographed from above (also with the other devices), with a camera that can be raised and lowered on a repro stand (Kaiser RTX tripod). The camera used is a modified Sony Alpha 7 camera (24.3 megapixels) (see above). The basic body of the light cylinder was commissioned from a locksmith. It consists of a cylindrical body made of sheet zinc with a door with a diameter of 45 cm and a height of 35 cm (Fig. 1a, b). In the metal lid (thickness 3 mm) there is a circular hole (diameter 8 cm) for the camera and lens. The lid also serves as a heat sink for the lamps. Eight Lumitronix LinearZ 280-26 elements with Nichia daylight LEDs (length 28 cm) were professionally glued to the underside of the metal lid as lighting and are supplied with power from a suitable power supply unit. Unfortunately, this article from Lumitronix is no longer available but there are suitable alternatives (see below). A polyoxymethylene disc (6 mm thick) suspended under the lid at a distance of 5 cm is used for colour-neutral light diffusion (Fig. 1d) in order to increase the proportion of scattered light and avoid cast shadows. Objects can be moved up and down in the cylinder by hand using a laboratory lifting platform (stainless steel) (Fig. 1c). A scale (10 mm) is moved into the image independently of the object (Fig. 1e, f). Focusing is done manually by first bringing the scale into focus. The insect is then moved into focus by rotating the lifting platform. In this method, the objects to be photographed are arranged by size beforehand in order to enable the most efficient and quickest possible workflow. Before photography, the moths are placed on plates made of roughened aluminum (see Box 2: background). These plates contain an insect needle with a short pipette tip attached to its head (Fig. 1c, e). This is filled with wax so that the objects can be easily fixed both with the pointed side of the needle (photograph of the upperside) and with a needle head (photograph of the underside). The purpose of this is to achieve

the greatest possible distance from the background so that it remains completely out of focus. Three xenon flash units (two Neewer NW570 and one NW635) are used for UV photography (Fig. 1c), which indirectly illuminate the object via the ceiling. The cover was removed from the units to allow UV radiation to escape during the flash (spectrum: Fig. 4f). Photographs are always taken with the door closed to ensure uniform lighting.

Light box for insect drawers

The light box for insect drawers (Fig. 2) was built from an aluminum profile system (15 mm thick) into which (previously used) reflective, scattering aluminum plates with a honeycomb-like surface structure were built, as used in conventional lamp construction. The box has external dimensions of 63 × 53 × 83 cm (WxDxH) and is therefore designed for the photography of insect drawers in standard format (51 × 42 cm). The roof consists of a 3 mm thick metal plate, which also serves as a heat sink for the LEDs. As in the light cylinder, Lumitronix LinearZ 280-26 elements (see above) are also used (eight units), which are arranged all around the edges (6 units) and two parallel in between (Fig. 2c). A hole measuring 20 × 16 cm (WxD) was sawn out in the roof. The reproduction tripod standing on top was equipped with a self-made base made of 30 mm thick aluminum profiles and enables photography through this base. The camera used is a Sony Alpha

Box 2. Background.

When choosing the colour for the background of objects, there seems to be a lot of choice. For example, the contrast to the object can be maximized or the background can have a colour that does not occur in the object (Ariño and Galicia 2005). On closer inspection, however, it becomes clear that when photographing a large number of different specimens and different species, it is far less obvious what the maximum contrast actually is and which colour never occurs. Coloured backgrounds as shown by Ariño and Galicia (2005) can be suitable for easily isolating objects afterwards, similar to green screen compositing. However, the technique can influence the colour of objects in the edge area due to reflections. In my view, strong background colours also distort a realistic colour impression of the object, since highly saturated colours such as dark blue rarely occur as a background in nature. Therefore, the choice ultimately boils down to a neutral background colour with a defined grey value, which is also often practiced. Even „white“ backgrounds in photography – provided they are not overexposed – are actually a very light grey. For example, when producing the plates for a book about all butterfly species in Germany (Settele et al. in press), a light grey with a uniform grey value of R=G=B of 225 was chosen for the background of the 60 plates. This allows a good representation of both dark and bright butterflies. The isolation of the individual objects with a light grey original background was easy to do with appropriate image editing software (Adobe Photoshop). What materials are suitable as backgrounds in photography? I compared different materials: 1) normal white printer paper treated with optical brighteners; 2) paper without optical brighteners (Schoellershammer artist paper); 3) a matt grey PVC film (Oracal No. 631 Light Grey); 4) polyethylene foam as used in insect boxes and 5) a matt aluminium surface – a mouse pad sawn into four pieces is used, which is available under various brand names (e.g. Vaydeer on amazon.de). A test chart was photographed at different magnifications and working distances with a daylight LED in the light cylinder (Suppl. materials 1–3). It was shown that all materials represent (approximately) a neutral grey in the VIS range (light visible to humans) – with the exception of the untreated paper, which has a colour cast. For the UV photography aspect, the same chart was photographed under UV radiation (Suppl. materials 1–4). This shows that both the treated normal paper and the PVC film absorb or transform a part of the UV radiation and therefore appear dark. For an almost colour-neutral photography in the UV+VIS spectrum, only plastics such as polyethylene (also polystyrene, for example) or metals (such as an aluminum surface in the example) are suitable. I chose aluminum because of its darker surface. A disadvantage of aluminum, however, is that the brightness changes depending on the distance from the light source (Suppl. materials 1–3) and complete standardization in relation to the background is not achieved. However, this has not yet posed a problem for practical applications because objects can be isolated (in image editing software) when assembling image panels in such a way that small differences in the grey values at the edges of the wings of the moths are not significant. Slight changes can also be seen in the PVC film, while paper and polyethylene show largely constant lightness values at all image scales. The effect is obviously related to the mattness of the surface.

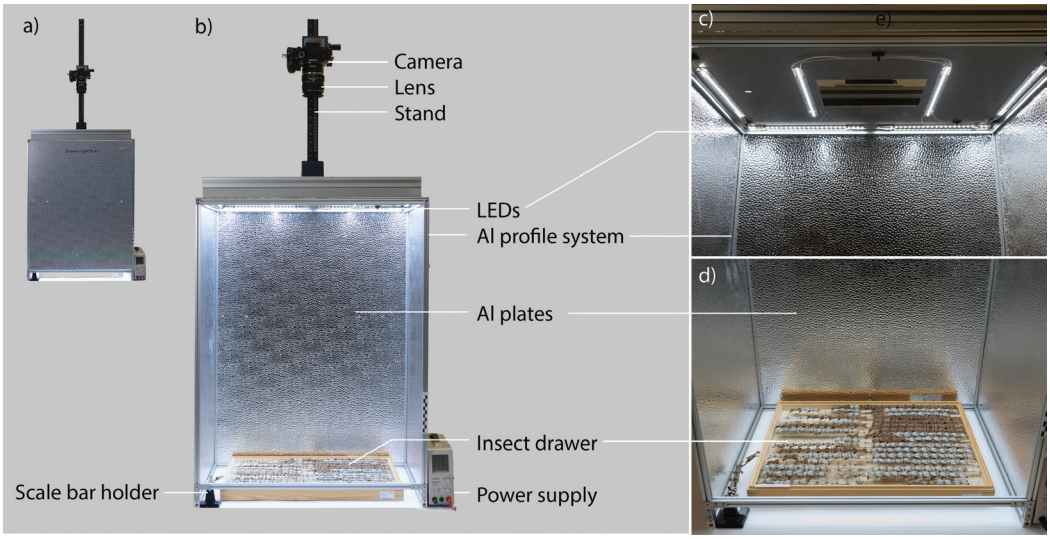

Figure 2. Light box for insect drawers. **a.** Overview with front panel attached (when photographed); **b.** Overview without front panel; **c.** Inside view of the lighting on the ceiling; **d.** Inside view of the photographed insect drawer with scale holder.

7R mark IV (61.0 megapixels), which is attached to a repro stand 124 cm above the insect drawer. The insect drawer can be pushed in and taken out from below with the front panel being attached (Fig. 2a). A scale (10 mm) is placed next to the drawer using a small tripod before the picture is taken. The printed inventory number of the drawer is also included.

Light hemisphere

As a cost-effective, lightweight and easy-to-make alternative to the light cylinder, the possibility of working with polystyrene hemispheres was tested. These are available in sizes with a diameter of up to 50 cm as decorative material (Rayher no. 3306400). Polystyrene has good reflective properties, including in the UV range. However, the material is translucent, so that on the one hand light escapes from the hemisphere and on the other hand light can enter from outside. Therefore, the hemisphere was covered with aluminum foil on the outside (Fig. 3). In the middle at the top there is a circular opening in which a metal ring is embedded (Meetory baking ring with a diameter of 8 cm). An LED strip was glued to the outside of this metal ring (Lumitronix Lumiflex 700 pro Sunlike), which is powered by a power supply unit. To make handling insects easier, a door was cut into one side with a hot wire, which can be raised and lowered using a pull rope (Fig. 3a, b). The height was adjusted to the working distance of 36 cm between the camera and the sample using two squared timbers wrapped in aluminum foil (height 7 cm). The light hemisphere was optimized for the photography of ethanol samples. The insects lie in a liquid, so that direct lighting from above leads to strong reflections on the surface (Fig. 8c). The reflections were reduced by covering the direct radiation of the LED strip with aluminum foil (Fig. 3c). The insects were distributed in a rectangular white ceramic bowl (size 25 × 17 cm, Meeden), covered in 70% ethanol and photographed. The area in the bowl in which

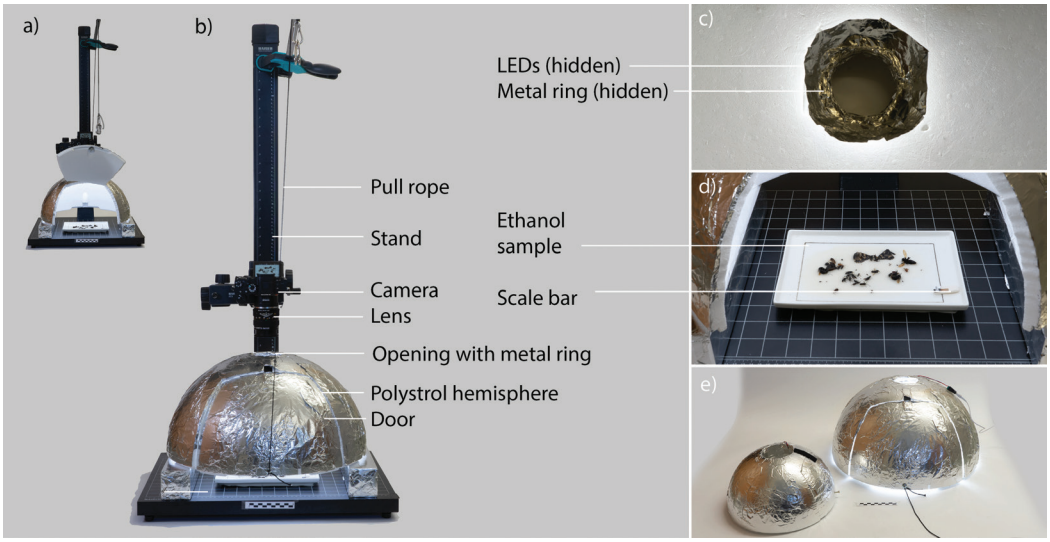

Figure 3. Light hemisphere. **a.** Overview with door open (lifted with pull rope); **b.** Overview with door closed (Scale 10 cm); **c.** Interior view with metal ring and LEDs; **d.** Interior view with metal ring hidden to avoid strong reflections on liquid; **e.** View of the photographed ceramic bowl with insects from ethanol sample; **f.** Hemispheres in different formats: diameter 30 cm and 50 cm.

the photograph is to be taken was marked in the proportions of the sensor (19.5 × 13 cm). As in the light box, a Sony Alpha 7R Mark IV is used as the camera, which is attached to a repro stand (see details above).

Results

Spectral measurements

Table 1 gives an overview of the measurements carried out in the three museums in Jena, Berlin and London. The complete measurements are documented in Suppl. material 2 (pdf) and Suppl. material 3 (xlsx). Figure 4 shows an overview of typical spectral patterns of different light sources with reference to daylight. LEDs (Fig. 4a–e) are typically characterized by a primary blue peak. Depending on the LED, the emitted spectrum is expanded with the help of certain chemical substances in the LED. In the case of bluish cold white LEDs, the blue peak is very pronounced (Fig. 4d, e), whereas in other LEDs it is moderately to significantly reduced (Fig. 4b, c). Daylight LEDs (Fig. 4a) are most similar to natural light in terms of spectral composition (CIE R_e = 98), while the CIE R_e values of the other LED lamps tested are between 45 and 82. The lowest CIE R_e values are achieved by the Supra Quartz Scanner and the Leica Z16 microscope because the spectrum deviates quite significantly from daylight – in particular due to an overemphasis on blue and an underemphasis on turquoise and red. Flash light could not be measured effectively due to its short pulse time. Instead, a continuous Xenon arc lamp was measured (Fig. 4f). It shows a balanced spectrum with a value of R_e = 87. Devices with fluorescent tubes (mercury vapour) show the typical spectral pattern with some clearly recognizable characteristic peaks that are typical of

Table 1. Quality of the light sources, based on spectral measurements in three museums (Berlin, Jena, London). The CIE R_a index (Colour Rendering Index) is based on the correspondence with 8 exemplary colours. The more meaningful and stricter **CIE R_e** index is based on the correspondence with 16 exemplary colours.

	Source	Colour temperature ca.	CIE R_a	CIE R_e
Daylight	Sun/overcast/daytime	5500–6500 K	>99	**>98**
Museum				
Ceiling lights in working areas	Mercury vapour	3000–3600 K	76–87	**64–84**
Exhibition lights (Berlin, London)	LED	2800–3100 K	79–83	**72–78**
New insect digitisation devices				
Light cylinder	Lumtronix Linear Z daylight LEDs	6100 K	99	**98**
Light box	Lumtronix Linear Z daylight LEDs	6400 K	99	**98**
Light hemisphere	Lumtronix Pro Sunlike	4600 K	98	**97**
Insect digitisation devices				
Arc lamp (Xenon)	same as flash	6200–6500 K	91	**87**
Mass digitisation (Berlin)	LED	3900 K	87	**82**
Leica Z16 microscope (Berlin)	LED	6900 K	76	**66**
Suprascan Quartz (London)	LED	4100 K	58	**45**
Kaiser Repro Light (Berlin)	Mercury vapour	4900 K	88	**81**
SatScan (London)	Mercury vapour	3800 K	76	**65**
SatScan (Berlin)	Mercury vapour	3600 K	85	**76**
Light Box with circle tube	Mercury vapour	4700–5300 K	79–87	**70–84**

Table 2. Information on distances between camera and object as well as on the uniformity of the distribution of light in the three lighting devices. Max. dev = maximum observed deviation of measurements.

	Distance		Irradiation (W m^{-2})			Pixel in tif image (R=G=B)		
	filter wheel – insect	sensor – filter wheel	Centre	Range	Max. dev.	Centre	Range	Max. dev.
Light cylinder (with diffusor)								
Scale 1:1	9.4 cm	+ 18.5 cm	16.58	16.39–16.55	1.1%	210	210–211	1.0%
Scale 1:1.5	14.4 cm	+ 18.5 cm	16.22	16.22–16.34	0.8%	219	219–222	1.4%
Scale 1:2	18.0 cm	+ 18.5 cm	16.61	16.61–17.23	3.7%	225	225–231	2.7%
Scale 1:2.74	26.0 cm	+ 18.5 cm	18.19	18.19–18.68	2.7%	227	227–232	2.2%
Scale 1:4.74	41.0 cm	+ 15.4 cm	21.05	20.76–21.25	2.3%	239	235–239	2.7%
Light box (no diffusor)								
	–	124 cm	10.97	11.12–11.48	4.7%		–	
Light hemisphere								
Ø 16 cm	–	36 cm	11.28	11.52–11.83	4.9%		–	
Ø 32 cm	–	see above	see above	12.79–13.31	20.0%			

mercury vapour lamps (Brehm 2017). Here, too, an almost continuous spectrum is achieved by adding certain chemical compounds (Fig. 4g, h). The CIE R_e values for the tested devices for insect photography reach 65 to 84. The resulting photographs reflect the differences in quality of the light used (Fig. 5); in particular, the photograph taken in the SatScan device is significantly inferior in quality to the other examples.

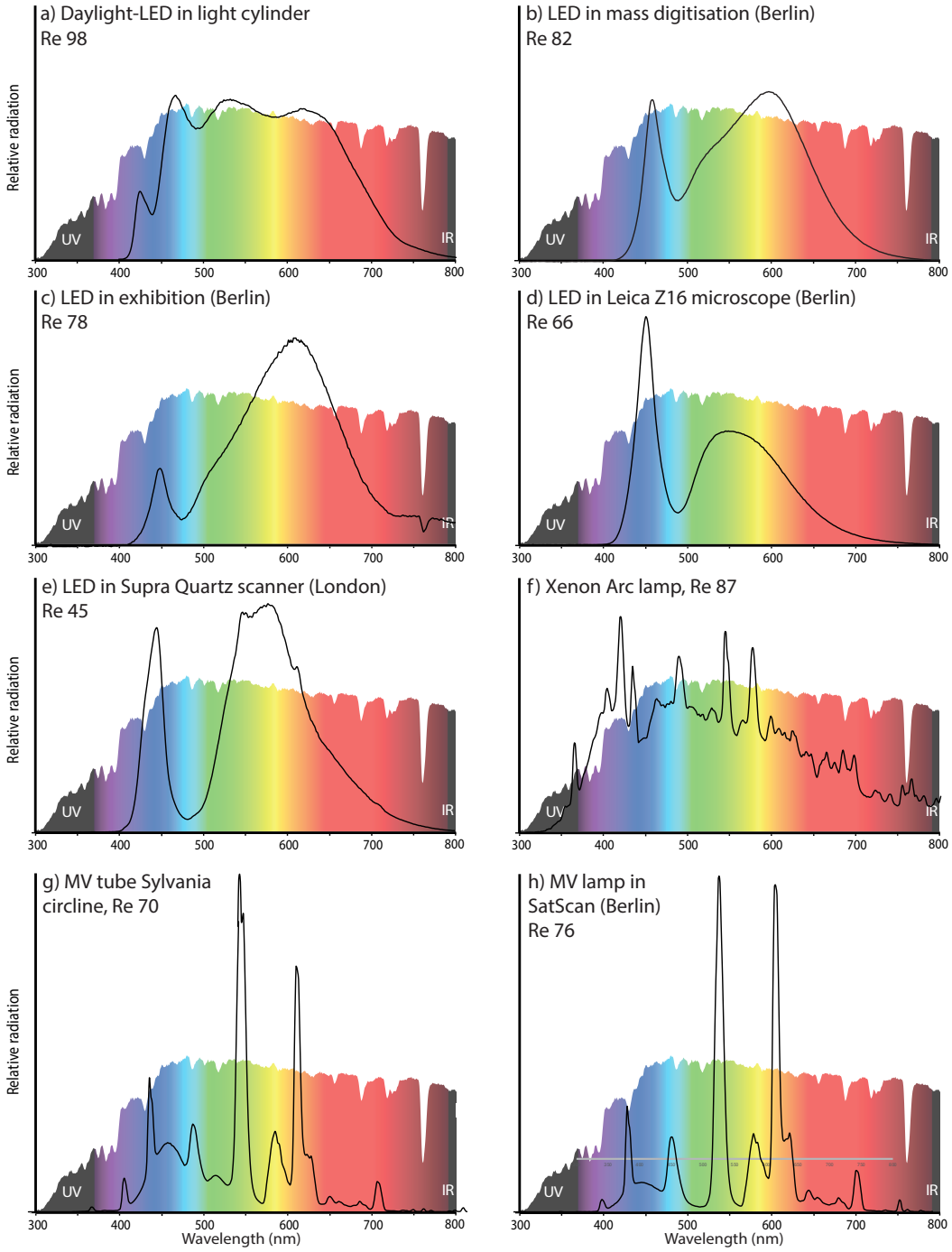

Figure 4. Overview of typical spectral patterns of different light sources with reference to daylight (coloured). **a–e.** LED light sources; **f.** Xenon arc lamp; **g, h.** Mercury vapour lamps. The R_e value is given in each case, which is > 98 in daylight. See Suppl. materials 2, 3 for detailed results.

Figure 5. Comparison of photographs taken in with different light sources. The images were standardized in terms of white balance and exposure (white reflectance standard set to RGB 241/241/241). They were saved in tif format but otherwise not modified. **a.** Shot in daylight (overcast sky); **b.** Shot in light box; **c.** Shot with SatScan (device in Berlin); **d.** Shot with Xenon flash. Note that monitors cannot reproduce all stored colour information of the Adobe RGB colour space and general limitations when reproducing images on displays and in print. See Suppl. material 4 for more detailed results and corresponding colour charts.

Light cylinder

The light cylinder ensures shadow-free illumination in the VIS range (Fig. 5a–d) with very high light quality. In the UV images, slight shadows can be seen due to the use of three flash units, especially in very large moths. With different image scales, the amount of incident light and also the distribution within the image section change. Very homogeneous light conditions are achieved at all image scales. The largest deviations (3.7% for irradiance and 2.7% in relation to the brightness of the pixels) were achieved at an image scale of 1:2. At larger image scales up to 1:1, the image section is smaller, which leads to greater homogeneity (only 1.1% for irradiance and 1.0% in relation to the brightness of the pixels). At smaller image scales, the distance to the light source increases, and with it the proportion of light scattered in the light cylinder, so that very small

deviations are measured here too (2.3% for irradiance and 1.7% in relation to the brightness of the pixels). Detailed results are documented in Suppl. material 1. In routine operation, the system makes it possible to photograph around 20–25 specimens per hour (VIS+UV). Naming, further processing of the image files and data management, require additional working time.

Light box

The light box enables evenly bright and shadow-free illumination in the insect drawer (Fig. 7) with very high light quality (R_e = 97, see above). The homogeneity of the lighting is very high overall – the maximum deviation of the five measured irradiance values is 4.7%. In routine operation, the system makes it possible to photograph around 25 drawers per hour, provided the boxes are available within reach next to the system. The image size of 61 megapixels allows a resolution of around 150 pixels per centimeter (ppcm) and thus detailed insights into a collection. Visible parts of small-print labels can be easily recognized. Naming, further processing of the image files and data management require additional working time.

Light hemisphere

The light hemisphere also enables shadow-free illumination (Fig. 8) with very high R_e values. The homogeneity of the illumination is high in the inner area of the hemisphere (diameter 16 cm – i.e., the area in which the bowl with samples is located). The maximum deviation of the five measured irradiance values is 4.7%. In an area with a larger diameter (32 cm), the brightness increases significantly towards the edge, with a deviation of 20% – but this range is not relevant in this specific example. The pure time for photographing a sample is about two minutes per sample (30 per hour). More working time must be taken into account for preparing the samples, as well as for naming, further processing of the image files and data management.

Discussion

Surprisingly bad light quality of museum devices

Measuring the quality of light sources has, on average, revealed a significantly worse light quality than I expected. It could be argued that further problems can occur during subsequent colour management, e.g. due to the possible incorrect and distorted display of colours in monitors. Suitable lighting can certainly not prevent such errors, but is not a source of error itself. Apparently, too little attention has been paid to the quality of light sources in photography and digitization. For example, Mantle et al. (2012) and Blagoderov et al. (2014) present a device for mass digitization with the Satscan, without mentioning the quality of the light source. Hardly any light source tested, other than the daylight LEDs, achieves the CRI value of more than 90 required by the Federal Agencies Digital Guidelines Initiative (2023). The light quality of the mercury vapour lamps reaches a maximum of R_e = 84, but in one case only 65 (SatScan in London). Although mercury vapour emits photons over a wide spectral range, it is not possible to achieve a spectrum without pronounced peaks. Due to environmental aspects, it can be observed that mercury vapour lamps are being replaced by LEDs in many places. This is also desirable in all areas where the recognition of colours plays a role, such as work rooms in museums where taxonomists work. Here, for example, the ceiling lighting at the NHMUK in London only achieves R_e values less than 70. This is all the more regrettable as some work rooms have no windows at all, which in my opinion also has a negative impact on general work in these rooms.

The measured LEDs vary considerably in terms of light quality. Satisfactory values are achieved in the exhibition area of museums, where LEDs are used in which the blue component is significantly reduced for conservation reasons and which therefore appear 'warm white'. Here, the focus is not on perfect colour reproduction – as is the case with street lighting, for example – but on protecting sensitive objects. Surprisingly poor R_e values are achieved by the Supra Quartz Scanner at the NHMUK in London and the Leica Z16 microscope at the Museum of Natural History in Berlin. In both cases, these are LEDs with a strong blue peak and a pronounced deviation from the daylight spectrum. It is difficult to understand why LEDs of this quality, which are unsuitable for colour reproduction, are used in otherwise expensive devices. Flash units perform very well in terms of colour quality with CIE R_e values of almost 90 and can be used without any problems. Extremely good CRI values are only achieved by the daylight LEDs presented here. R_e values of >90 or >95 are now available on the market for a number of LEDs according to manufacturer information. In more recent works such as by Steinke et al. (2024), lighting systems with daylight LEDs are described. Daylight LEDs were still a niche product around 2020, but they are now easy and inexpensive to obtain. However, many products are only on the market for a short period of time. For example, the daylight LEDs used in the light cylinder are no longer available in this form; however, they can easily be replaced by LED strips of equivalent quality (e.g. from Lumitronix). The results suggest that daylight LEDs should in principle be used in all applications in standardized photography and digitization. I recommend not relying on manufacturer information alone, but to carry out spectral measurements if in doubt. Converting existing devices to other LEDs should generally be possible.

Performance of the new devices

All three lighting devices serve their respective purpose, although each has a different basic shape (cylinder, cube, hemisphere). The basic principle is to illuminate from many sides, which is made possible by scattering the light from the inside. The aim of the lighting is to obtain as high a proportion of scattered light as possible, with perfect conditions occurring outdoors on a cloudy day. This ensures that there are no unwanted shadows that can lead to problems in image evaluation. The devices presented do not, however, enable reflection-free photography, but in the light cylinder and in the light hemisphere these "specular" reflections are greatly reduced by the use of diffusers (Fig. 8). The light box is not (yet) optimized in terms of reflections, because direct reflections hardly occur in Lepidoptera due to the fine scales on their bodies. However, if other groups of insects are to be photographed, a diffuser could also be mounted under the ceiling so that, for example, on the shiny surfaces of beetles, no individual LEDs can be seen, but instead a more homogeneous, brighter surface.

In all devices, light is not allowed to leak out in large quantities (energy efficiency and uniformity) or from the outside to the inside, for example when the devices are operated in a room with windows. Another approach is taken by Steinke et al. (2024), for example – here the lighting is positioned freely in the room. This is particularly useful for applications that require a lot of space, and in this case practically the entire room is a large 'box'. One advantage of this method is the freedom of movement without restrictions. A disadvantage is that it takes up an entire room, requires a relatively large amount of light and energy, and one is unable to carry out UV photography for safety reasons. The light cylinder has proven itself in photographing individual moths over the past four years. The workflow described with manual focusing, an independently adjustable scale and the insertion of moths on individual aluminum pads, works well. I have produced many thousands of standardized images in this way. I had previously photographed with a Kaiser reproduction system

Figure 6. Photographs taken in the light cylinder: **a.** Male and **b.** female of *Gonepteryx rhamni* (VIS and UV); **c.** Male and d) female of *Lycaena alciphron gordius* (each in the VIS and UV range). In the UV range, patterns become visible in the males of both species through UV photography that cannot be perceived by humans.

in which light was shone on the object from the left and right. With this method, two shadows were always visible, which is no longer the case with the new methods described here. Shadowless images make subsequent image processing (e.g. for colour plates) much easier, as isolating objects is efficient and precise. Further images, in addition to the images shown in Fig. 6, can be found, for example, in a book that covers all of Germany's butterflies (Settele et al. in press). Since 2020, thousands of representatives of the Geometridae, Arctiinae, Sphingidae and Saturniidae have been photographed for research projects in Ecuador and Peru. The standardized photographs allow the reliable quantitative evaluation of traits such as brightness and contrast for each individual as well as automated recording of data on body size – and this for a spectral range that also includes UV. Working in the light cylinder is somewhat difficult due to the limited space (diameter 45 cm). Future cylinder models should therefore be dimensioned somewhat larger. The light box was only recently put into operation in combination with a new Sony alpha 7R IV, so there is no long-term experience with it yet. The results are very promising, however. Initial tests have shown that up to 30 boxes can be photographed per hour if they are placed in readiness next to the device. A major advantage of the method is the high throughput and also the manageable costs – especially compared to solutions with medium format cameras and giant sensors. The image size of 61 megapixels allows details on labels to be recognized – ten years ago, such values were still outside the consumer-grade cameras described by Holovatchov et al. (2014). In fact, the effective resolution with the camera described is close to 61 megapixels. If an even higher resolution needs to be achieved (e.g. with very small insects), it is also possible to take four images per box. In the Phyletic Museum Jena, for example, there is a system with four individual boxes per box that can be photographed individually in this way. The Satscan devices in use in some large museums produce very large images (Mantle et al.

Figure 7. a. Photograph of complete insect drawer (Inventory number PMJ Hex-1262 from Brettschneider collection). Scale bar: 1 cm, taken in light box with Sony alpha 7R mark IV with 61 megapixels; **b.** Inset with details of single labeled butterfly specimens.

2012). However, only a maximum of around 10 scans per hour can be produced here, at a much higher purchase price and with an image quality that shows major weaknesses, especially in the reproduction of red tones (Fig. 5c). Cheap webcams with a very high nominal resolution are not comparable and it is hopeless to expect a comparable performance to that of full-format sensors.

Photographing entire drawers is useful in order to begin recording collections where they do not yet exist. This appears to be an important option, especially in smaller museums, because the resources for individual digitization are not available. Here, it is often the case that hardly any changes occur in historical collections over many years, so that the images represent the current status for a long time. Another advantage is that negative changes are documented, for example due to pest infestation or theft. For parts of the collection, however, where a lot of work and sorting takes place, photographing entire boxes is less useful. Individual recording is particularly suitable for such parts of the collection. The light hemispheres are a simple, inexpensive alternative that anyone can build. Their appearance, however, has a more "DIY" character, but this does not have to be a problem. The hemispheres, like the light cylinder, are relatively cramped. For some objects, the height of the hemisphere itself is not sufficient, so the sphere can be placed on a base, which can be made of polystyrene or wood wrapped in aluminum foil, for example. Shielding the direct

Figure 8. a. Photograph of ethanol sample taken in light hemisphere with indirect LED lighting. Scale bar: 1 cm, taken with Sony Alpha 7R IV at 61 Megapixels; **b.** Enlarged section with beetles; **c.** Comparison with direct lighting.

LED radiation using aluminum adhesive tape enables low-reflection photography of wet samples. Further work will have to show whether, and to what extent, it is possible to identify material based on the photographs. The high resolution achieved in any case allows the taxa to be identified by order, but usually at a much higher taxonomic level.

UV photography: Unrealized potential in digitization

UV photography enables the documentation of colour patterns in insects and other objects that go well beyond the usual RGB colour space. This is sometimes impressive, as in the case of male brimstone butterflies (Pieridae: Coliadinae) and many copper butterfly (Lycaenidae: Lycaeninae) species, where patterns previously not visible to humans appear (Fig. 6). But even in more inconspicuous species, it is often worthwhile to record the UV information. To my knowledge, digital colour information in digitization projects is recorded practically 100% in the RGB colour space. The reasons for this seem obvious: RGB colour spaces are perfectly red, green to human needs, all devices – from digital cameras to monitors – work with the three colour channels red, green and blue. The downside, however, is that this view is very anthropocentric. The RGB colour space is certainly appropriate for almost all types of cultural assets, but it is questionable for biological subjects and the digitization of biological collections. A comparison: Would it make sense to document the vocalizations of grasshoppers, bats and elephants only in the sound range that humans can hear? The question seems absurd, because it is of course clear that ultrasound and infrasound are relevant for these organisms, and that biological work naturally records these frequencies that are inaudible to the human ear. The same question applies to vision: Why

is the UV range largely ignored when digitizing collections? Humans cannot see in the UV range – but the vast majority of species can, in particular most arthropods, but also most groups of vertebrates (with the exception of most mammal species including humans), in particular many bird species are able to perceive UV (Ödeen and Håstad 2010). Fig. 9d shows an example of the spectral range covered by birds (example: Eurasian Blue Tit, *Cyanistes caeruleus* (L.)) and insects (example: Honeybee, *Apis mellifera* L.). The figure shows that a modified camera has spectral sensitivities that are close to those of an insect eye (trichromats: UV, blue and green) and those of a bird (tetrachromats: UV, blue, green, red). With the help of false-colour images, these can be recreated, for example, in the respective 'viewpoints' (Fig. 9d).

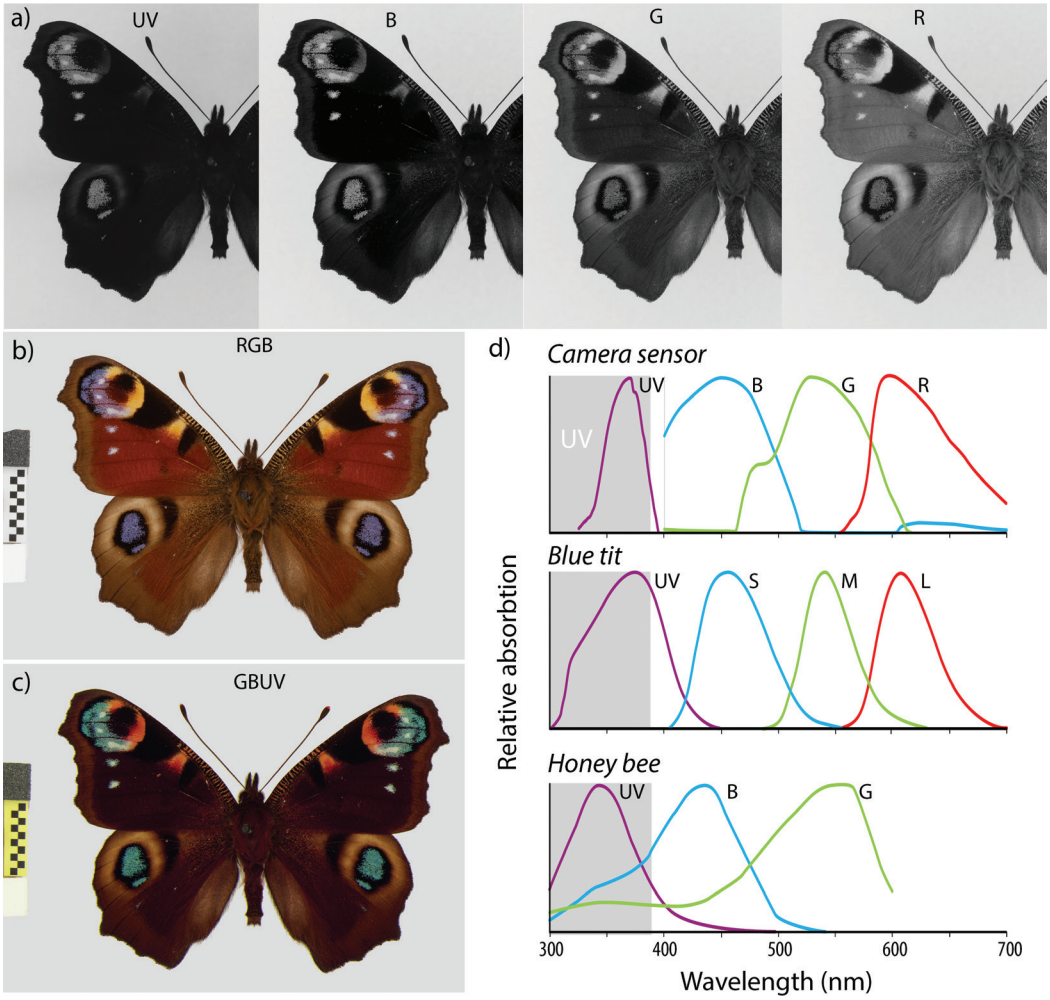

Figure 9. a. UV photography provides an additional fourth colour channel (UV), in addition to the usual channels B = Blue, G = Green, R = Red; **b.** Normal RGB image; **c.** False colour image with colour information GBU, shown in the usual RGB colour space; **d.** Measured relative sensitivity of a camera sensor in four colour channels (modified Sony Alpha 7) compared to the relative absorption of the cones in a bird's eye (Eurasian Blue tit: Hart and Vorobyev 2005) and in an insect (Honeybee: Briscoe and Chittka 2001). Eurasian Blue tit: UV, S, M, L refer to the ultraviolet- (UVS), short-wavelength- (SWS), medium-wavelength- (MWS) and long-wavelength-sensitive (LWS) single cones, respectively.

One reason that the recording of brightness information in the UV range has been neglected is certainly that the same systems that are used for photographing 'normal' cultural assets simply cannot be used. The recording of UV data is currently (still) a 'tinkering task', and efficient concepts and tools for the evaluation of data seem to be largely lacking. The necessary cameras that are comparable in comfort and price to normal RGB cameras cannot yet be bought off the shelf. However, as the example above also shows, it is not at all impossible to produce high-quality UV images with reasonable financial means (Prutchi 2017). In certain cases it also seems worthwhile to record other patterns, such as UV-induced visual fluorescence (Brecko et al. 2016).

Conclusions

The present study shows some astonishing deficits in the quality of light commonly used for the photography and digitization of insects, which very likely applies to other areas in biology and beyond. Future studies should show whether and what effects poor light quality has on the results of e.g. lightness measurements of insects in quantitative studies. Based on the insight of this study, digitization programs should fundamentally check the quality of their lighting and then install better light sources if necessary. LEDs with daylight quality are now readily available and they represent a long-lasting, ecologically acceptable and high-quality alternative to existing systems with poor light quality. The additional costs compared to 'normal' LEDs are insignificant compared to the higher image quality achieved. Spectral measurements can provide final certainty, because the quality of light cannot be assessed by eye. The recording of colour patterns in the UV range enables the documentation of a biologically essential component of the electromagnetic spectrum. The UV range should therefore play a much greater role in digitization programs, as well as in ecological analyses, than it has done until now.

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Supplementary material 1

Light cylinder: Measurements at different scales and light homogeneity; Light box & Light hemisphere: Light homogeneity

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Data type: pdf

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Supplementary material 2

Spectral measurements and Colour Rendering Index (CRI)

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Data type: pdf

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Supplementary material 3

Spectral measurements and Colour Rendering Index (CRI)

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Supplementary material 4

Moth box and colour chart images in different lighting settings

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Data type: pdf

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