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THE LIGHT-DOSIMETER – A NEW DEVICE TO HELP ADVANCE RESEARCH ON THE NON-VISUAL RESPONSES TO LIGHT

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Abstract

Research on the non-visual responses to light under real-world conditions has been hindered by the lack of suitable measuring devices. Here, we present a novel, portable and miniaturised light-dosimeter attached to a spectacle frame, taking measurements in the near-corneal plane. The recorded data is processed with the help of the custom-made software package Lido Studio. In addition to commonly used metrics such as illuminance and correlated colour temperature (CCT), it also provides metrics standardised in CIE S 026:2018. Data can be analysed directly in Lido Studio or exported as a PDF report or a comma-separated values (CSV) file for further in-depth time-series analyses. The Federal Institute of Metrology (METAS) optics laboratory (Bern-Wabern, Switzerland) assessed the light-dosimeter's spectral and geometric properties. Subsequentially, the team at the Centre for Chronobiology (Basel, Switzerland) confirmed that measurements performed with a light-dosimeter were comparable to those from a commercial spectroradiometer.

Keywords: Non-visual responses to light, light dosimetry, light-dosimeter, light exposure.

1 Introduction

When light impinges on our eye's retina it triggers both visual and non-visual responses with profound influence on our behaviour, health and wellbeing. Lighting research on visual responses has a long tradition, and measuring devices are relatively easy to obtain. In contrast, lighting research on non-visual responses gained traction fairly recently (~20 years ago), when a critical photoreceptor, the intrinsically photosensitive retinal ganglion cells (ipRGCs), was newly discovered in mice and then confirmed in humans (Berson *et al.*, 2002; Hattar *et al.*, 2002). While these photoreceptors and the human body's capacity to process light evolved under the natural light-dark cycle, human beings recently started spending most of the day indoors (Klepeis *et al.*, 2001; Leech *et al.*, 2002; Schweizer *et al.*, 2007). In a building, daylight is filtered through window glass and supplemented or replaced with electric light. Thus, indoor light is usually lower in intensity and different in light distribution and spectral composition than natural light outdoors. Furthermore, artificial light extends the availability of light to the natural dark period, often negatively impacting human health in various ways (Stevens *et al.*, 2014; Blume *et al.*, 2019).

In the years that followed the ipRGCs' discovery, there was no consensus. Different spectral sensitivity functions and metrics were used, including photometric quantities, which were unsuitable for non-visual stimuli. Only when the international standard CIE S 026:2018 was published in 2018, the research community was provided with a shared system for metrology of optical radiation to be used with regard to non-visual responses to light (CIE, 2018). In 2020 a group of renowned scientists published first recommendations for a healthy indoor light exposure reacting to a perceived need for guidance (Brown *et al.*, 2020). However, suitable measuring devices to reliably collect the required ambulatory data are still scarce, despite being viewed as key for acquiring new knowledge in the field (Münch *et al.*, 2020). Such devices need to provide information about the spectral composition of the radiation, its amount, and also the timing and duration of the exposure, i.e., they must be able to capture “light history”. Aiming to help fill this gap, we developed the light-dosimeters, providing these features in a small-scale format suitable for field testing.

2 Method

2.1 Conceptualisation

We developed a novel concept for measuring light[1] using a multidisciplinary approach. In 2018 a team from Lucerne School of Engineering and Architecture (Horw, Switzerland) consisting of experts in the field of electronics, software development, industrial design and light and health started its work. This allowed for a holistic view on the development of the device, as decisions taken in one discipline influenced work to be done in other disciplines.

At the start, we interviewed seven potential future users of such a device to find out their requirements e.g., light levels, wavelength range, recording intervals and additional desirable functionalities. In addition, the features and performance characterisations and assessments of similar devices were studied (Price *et al.*, 2012; Price *et al.*, 2017). Based on the information gathered, we developed a list with “must-have” and “nice-to-have” requirements, subsequently used as a guide throughout the project.

Simultaneously, a thorough evaluation of commercially available light sensors took place. After some consideration, we decided to use a light sensor with six optical channels covering the wavelength range 400 nm to 1 000 nm. Our spectral appraisal of the channels was backed by the METAS optics laboratory (Bern-Wabern, Switzerland). It was also established that the light sensor was able to measure light levels just below 1 lx. We appreciated that a multi-channel sensor had a lower energy consumption due to it generating a smaller data volume than a spectral light sensor. This allowed for a smaller, lighter battery enabling the miniaturisation of the device. Additionally, the integration time of a multi-channel light sensor is shorter at low light levels compared to a spectral light sensor. Lastly, simulations of the latest CIE spectral sensitivity functions according to CIE S 026/E:2018 (CIE, 2018) using CIE Standard Illuminants A, D65, B1-B5, BH1, RGB1, V1 and V2 with the selected multi-channel light sensor were deemed satisfactory, despite the calculations generating some negative values. Figure 1 provides a graphic representation of the simulation results under CIE Standard Illuminant D65 as an example.

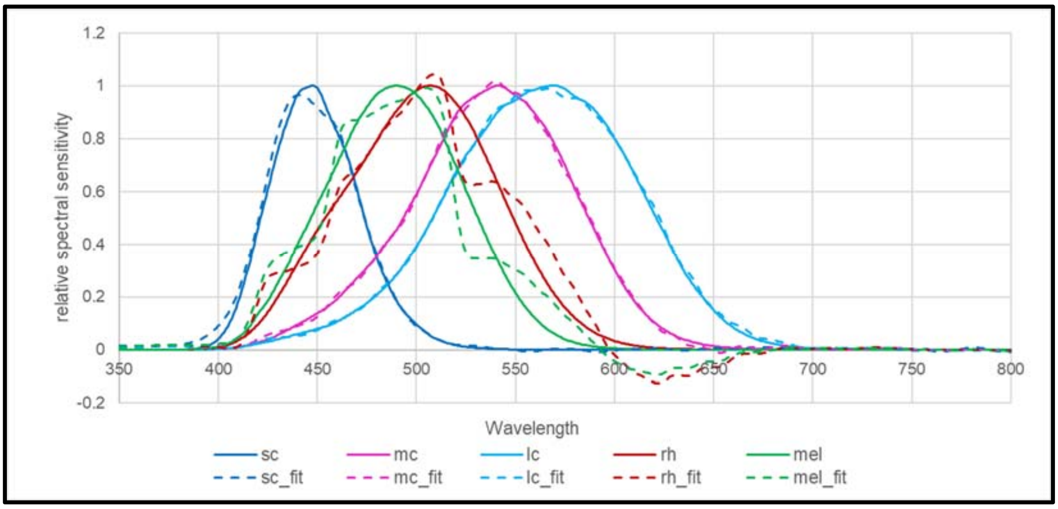

Figure 1 – Simulations (dashed lines) of the five spectral sensitivity functions (solid lines) according to CIE S 026/E:2018 under CIE Standard Illuminant D65

1 Strictly, a light-dosimeter measures radiation, not light. However, as it measures radiation in the visible range, terms like “light exposure” are used instead of “radiation exposure”.

2.2 Design

As a starting point for the design concept, the variation of measurements taken at different positions was tested. Illuminance was measured with five modified light data loggers (HOBO UA-002-64, onset, USA), whose light sensors had been replaced with silicon PIN photodiodes (VEMD5510C, Vishay, USA). Instead of attaching the photodiodes directly to the data loggers, they were connected to cables which were attached to the data loggers. Two photodiodes were then attached to a pair of glasses (one in the centre and one at the side), one to a bracelet and two to clips. This allowed measurements at five different positions to be taken simultaneously (Figure 2). These measurements were then compared with measurements (vertical, at the eye) using an illuminance meter (T-10, Konika Minolta, Japan). The results confirmed findings from previous studies (e.g. Aarts *et al.*, 2017) that the difference in the illuminance levels recorded were quite striking for some settings (Figure 3). Measurements taken at eye level were most closely related to those taken by the illuminance meter.

Based on these results our preference was to develop a device capable of taking measurements at eye level, despite user acceptance likely being better in less obvious positions like the wrist or chest. Informal discussions with the project partners and additional experts in the field of light and health supported this preference. Measurements in the near-corneal plane are viewed as the best available proxy to retinal irradiation by most researchers (e.g. Münch *et al.*, 2020). With regards to the exact position of the sensor, we decided against a solution with a light sensor in the centre of a test person’s face, as the gain in accuracy was not sufficient to outweigh the expected lower user acceptance due to the prominent spot.

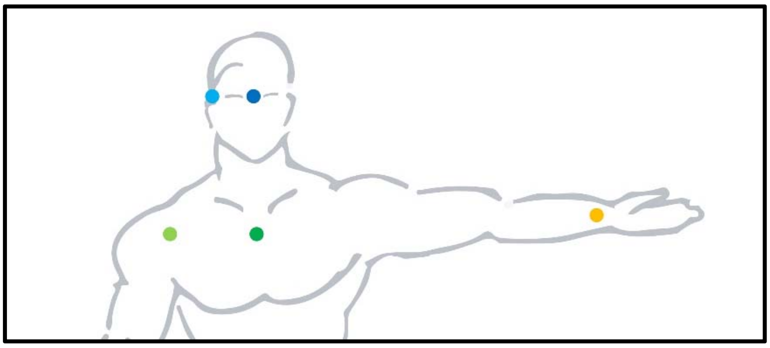

Figure 2 – Measuring points used in the data logger analysis

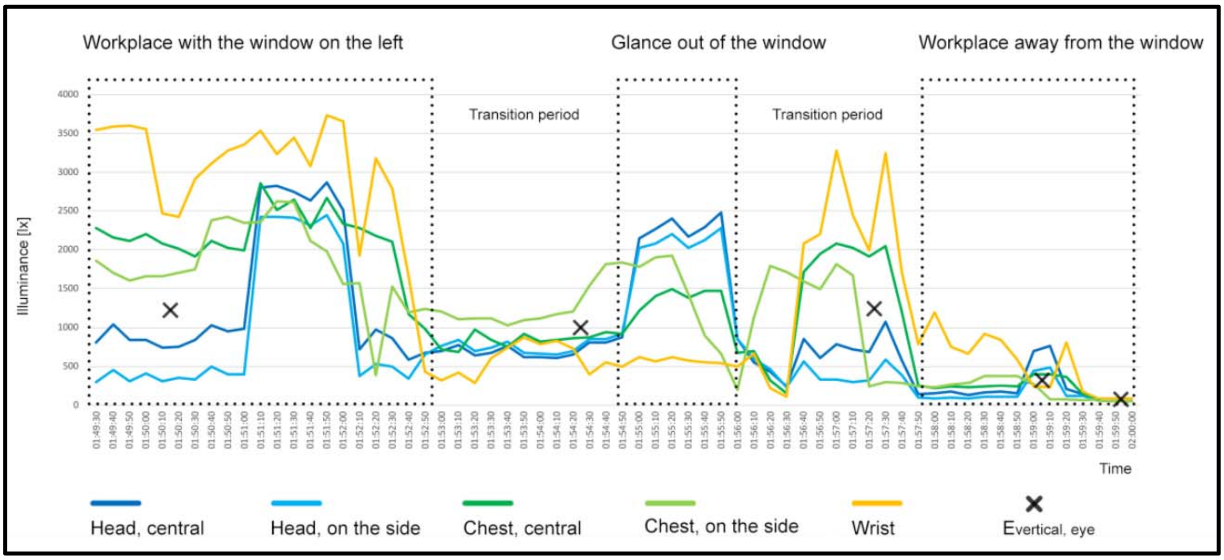

Figure 3 – Example of measurements taken at different measuring points for comparison

2.3 Hardware

After this initial phase of gathering information, team members knowledgeable in hardware, firmware and industrial design collaborated on developing the various elements of the device. Figure 4 shows the solution from an electronics perspective, i.e., the arrangement of the various components on a printed circuit board (PCB) as used in the final version with the light sensor at a 90° angle on the left. Among other things, the PCB hosts:

- an acceleration sensor, which tracks the tilt of the device, i.e., the angle of a test person's line of sight, if the light-dosimeter is worn at a spectacle frame,
- a push-button, which can be used to mark events as pre-defined by the lead investigator, e.g., the actual beginning and end of a test series, and ad-hoc events that need to be documented, and
- an RGB LED, which indicates e.g., a device's battery status.

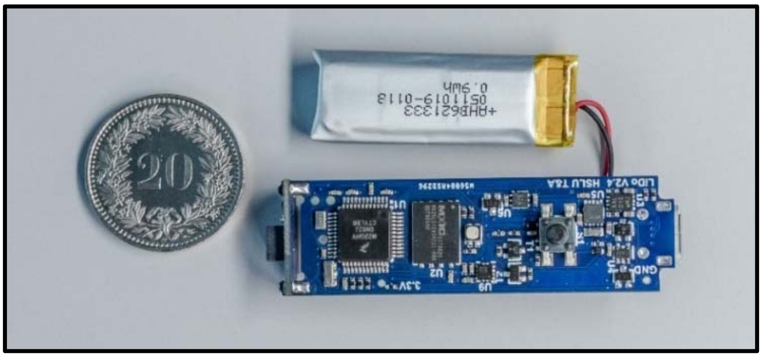

Figure 4 – PCB with key components and battery with a small Swiss coin (⌀ 21.05 mm) next to it for size comparison

A bespoke casing was designed to house the electronics, the rechargeable battery and the infrared cut-off filter and diffusor, which cover the light sensor (Figure 5). After different 3D printing materials were assessed, we decided to use Polyamid 12 (PA 12). As this material is opaque, a short fibre optic cable was used to make the light of the RGB LED visible. In addition, a bespoke mounting was designed, so that the device can be taken off during a recording if required (see the left of Figure 5). This mounting (also 3D printed with PA 12) can be attached to most spectacle frames and other frames, e.g., those of eye tracking devices.

The light-dosimeters were programmed to take measurements in 10-second intervals, with each measurement having a unique timestamp. The specification of the final in-house manufactured devices is summarised in Table 1.

Figure 5 – Light-dosimeter un-attached and attached to a spectacle frame

Table 1 – Specification of the light-dosimeters

Size of the casing	58 mm × 20,6 mm × 16 mm
Weight of the device	~27 g
Battery life	~7 days
Battery charging time	~2 hours
Memory size	~300 days
Wavelength range	VIS 380 nm to 780 nm
Measurement range	~5 lx to 100k lx
Interface	Micro USB

2.4 Calibration

Each light-dosimeter was calibrated in a specifically designed setup using the following equipment:

- a spectroradiometer (specbos 1201; JETI Technische Instrumente GmbH, Germany),
- an integrating sphere (AvaSphere-200; Avantes BV, the Netherlands),
- a reference light source (64634 HLX; Osram GmbH, Germany),
- an infrared cut-off filter (item number 53-710; Edmund Optics GmbH, Germany), and
- a personal computer/laptop running a National Instruments LabVIEW programme.

Figure 6 shows a block diagram of the calibration setup. After the calibration, each light-dosimeter ran through a series of tests. First, the performance of the light sensors was checked against simultaneous measurements taken by a spectroradiometer (specbos 1201; JETI Technische Instrumente GmbH, Germany) under an incandescent light source, a LED, a fluorescent light source and daylight. Then the performance of the devices' acceleration sensors was checked.

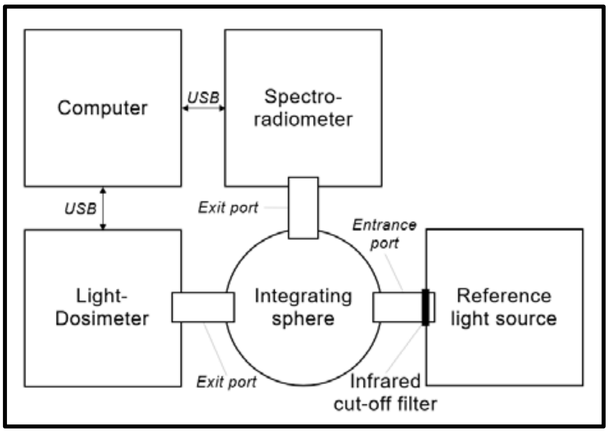

Figure 6 – Block diagram of the calibration setup

2.5 Software

Using Microsoft Visual Studio 19 Enterprise Edition, we developed the software package Lido Studio, which runs on a computer with Windows operating system. On its graphical user interface, the lead investigator enters the details of the planned test series (e.g., its time frame and test persons' details) and activates the light-dosimeters to be used. After collecting data, the investigator de-activates the light-dosimeters and then downloads the data in Lido Studio, which stores it in a local database. Using the software, initial analyses can also be run to display charts and plots instantaneously (Figure 7). The user can adjust the view to what is required, e.g., de-selecting certain metrics, choosing specific time frames, and selecting a logarithmic scale. The selections made on screen can be turned into a PDF report, the plots saved as images and the data exported as a comma-separated values (CSV) file for further analyses (e.g., in Microsoft Excel, MATLAB, Python, R).

The Lido Studio provides time series data for the event marker and the following metrics:

- α-opic irradiance ($E_{e,\alpha}, E_{\alpha}$) according to CIE S 026/E:2018 (CIE, 2018),
- α-opic equivalent daylight (D65) illuminance ($E_{v,\alpha}^{D65}$) according to CIE S 026/E:2018 (CIE, 2018),
- illuminance (E_v),
- correlated colour temperature (CCT) and Duv (Ohno, 2014) and
- tilt angle (between -90° and +90°).

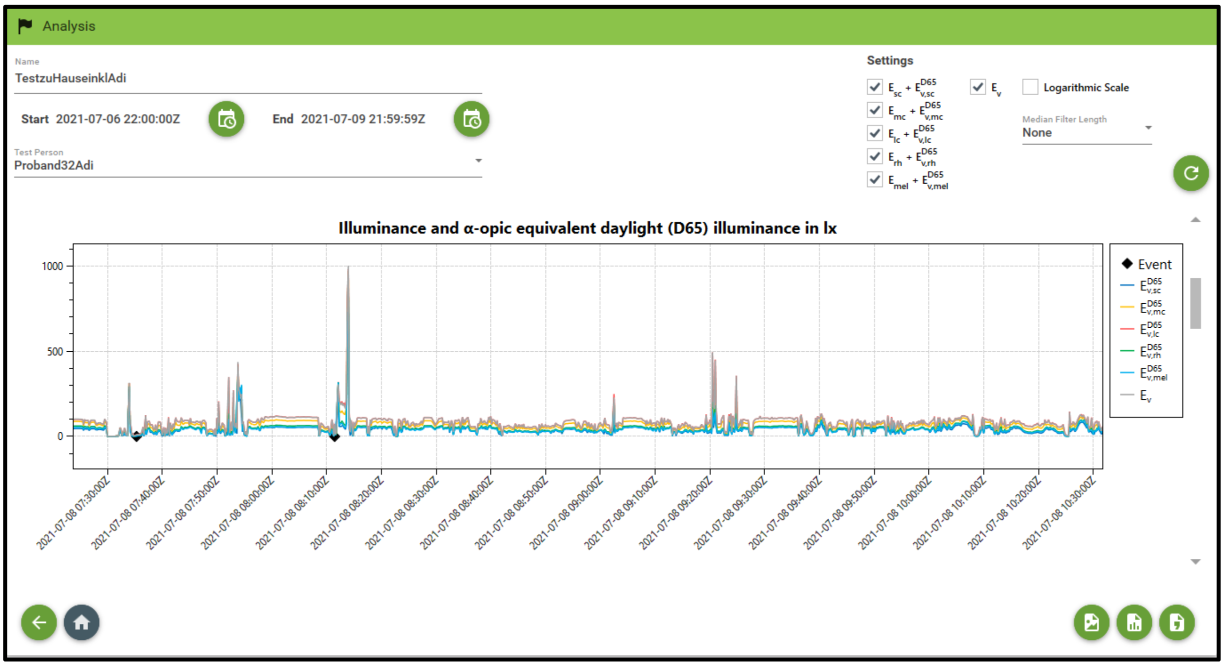

Figure 7 – Screenshot of the data analysis view in Lido Studio

2.6 Initial measurements

Several light-dosimeters were tested with regards to their spectral and geometric properties in the METAS optics laboratory (Bern-Wabern, Switzerland) in early 2021.

In spring and early summer 2021 the light-dosimeters underwent a trial period. Team members from Lucerne School of Engineering and Architecture (Horw, Switzerland) used the light-dosimeters to investigate light exposures over several days in real-life settings. We mainly wore the devices ourselves or took measurements by fitting them in a specific location.

Team members at the Centre for Chronobiology (Basel, Switzerland) deployed a light-dosimeter as part of an ongoing investigation of the spectral determinants of pupil size under real-world conditions.[2] Three healthy participants were involved in the tests: Two female subjects (24 and 25 years old) and one male subject (57 years old). The corresponding datasets were labelled according to the participants' ID "SP025", "SP029" and "SP033". Specifically, we compared measurements taken by a light-dosimeter with those taken by a small spectroradiometer (STS-VIS; Ocean Insight, USA). This was done in a field-compatible ambulatory setup in which the light-dosimeter was mounted on an eye tracker frame (Pupil Core; Pupil Labs, Germany) and the STS-VIS was mounted on a participant's forehead facing forward (in a 15° angle below the horizontal). The data was collected in 10-second intervals and binned into 1-minute averages

2 Ethical approval had been granted from the cantonal ethics commission: Ethikkommission Nordwest- und Zentralschweiz, project ID 2019-01832.

of melanopic irradiance. Testing took place across three experimental sessions of an approx. 1-hour experiment protocol in varying indoor and outdoor light conditions. Values below 5 mW·m^{-2} were excluded.

3 Results

3.1 Spectral and geometric properties

The tests in the METAS optics laboratory (Bern-Wabern, Switzerland) found that the deviations of α-opic equivalent daylight (D65) illuminance and α-opic irradiance were in the order of 10 % for all white light sources and the deviation of illuminance was less than 5 % for white light sources (Figure 8). Furthermore, the deviation of CCT was smaller than 100 K for CCTs below 4 500 K and smaller than 400 K for CCTs above 4 500 K. Figure 9 depicts the absolute CCT values measured.

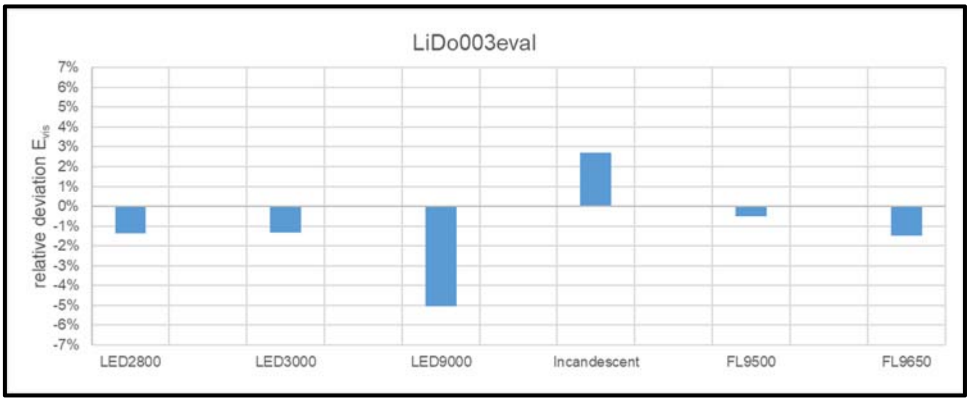

Figure 8 – Relative deviation of illuminance as measured by METAS

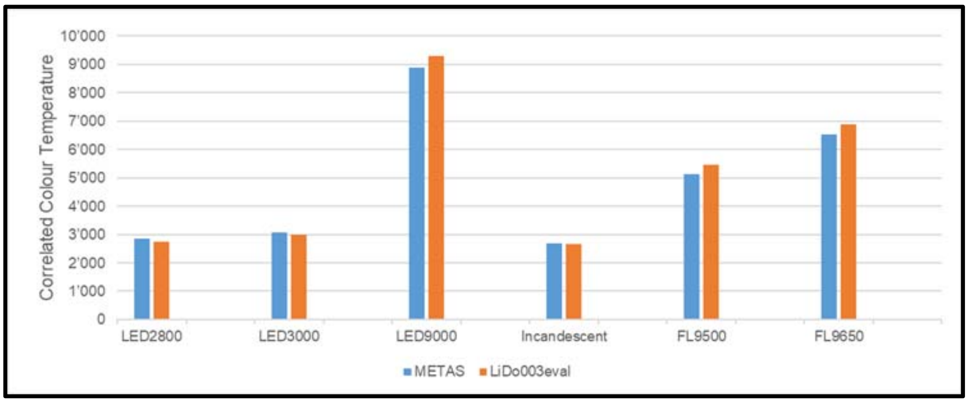

Figure 9 – Correlated colour temperature (CCT) as measured by METAS

3.2 Anecdotal trial period evidence

The trial period offered team members from Lucerne School of Engineering and Architecture (Horw, Switzerland) a chance to familiarise themselves with the light-dosimeters and the Lido Studio. We found lower than expected indoor light levels at workplaces, when measured in the near-corneal plane, and negative average tilt angles. A key learning from the self-experiments is that keeping a diary is a must. We would suggest the following entries as a minimum: Date, time, event marker pressed (yes/no), and notes, e.g., in case of a change of location and removal of the device. We would also suggest that a test person is given clear instructions regarding the handling of the device, the use of the event marker, and the keeping of the diary. Furthermore, they should be provided with some background information about the non-visual responses to light, as wearing a light-dosimeter in real-life settings led to a lot of questions and interesting conversations. Children as young as two years old noticed them and asked about their purpose.

3.3 Physiological measurements and validation with commercial spectroradiometer

The left panel of Figure 9 displays the timeline of near-corneal light exposure in one experiment session (SP033) at the Centre for Chronobiology (Basel, Switzerland). Interestingly, a small commercial spectroradiometer (STS-VIS; Ocean Insight) and a light-dosimeter show homogenous variations in melanopic irradiance across the experiment session. As depicted on the right side of Figure 9, 1-min averages of melanopic irradiance derived from the light-dosimeter were highly correlated with those derived from the small commercial spectroradiometer (Figure 9; r = 0,92, p < 0,001, Pearson coefficient). These results indicate that the measurements of the two devices were comparable. Additionally, near-corneal melanopic irradiance measured by the light-dosimeter was related to pupil size measurements derived from a Pupil Labs eye tracker. The results are illustrated in Figure 10. Notably, within-subject pupil diameter varies substantially at low irradiance levels, displaying much more stability at high levels. In addition, the data shows distinct dose-response curves for each subject, indicating that variation in pupil size can successfully be described as a function of near-corneal melanopic irradiance measured by a light-dosimeter.

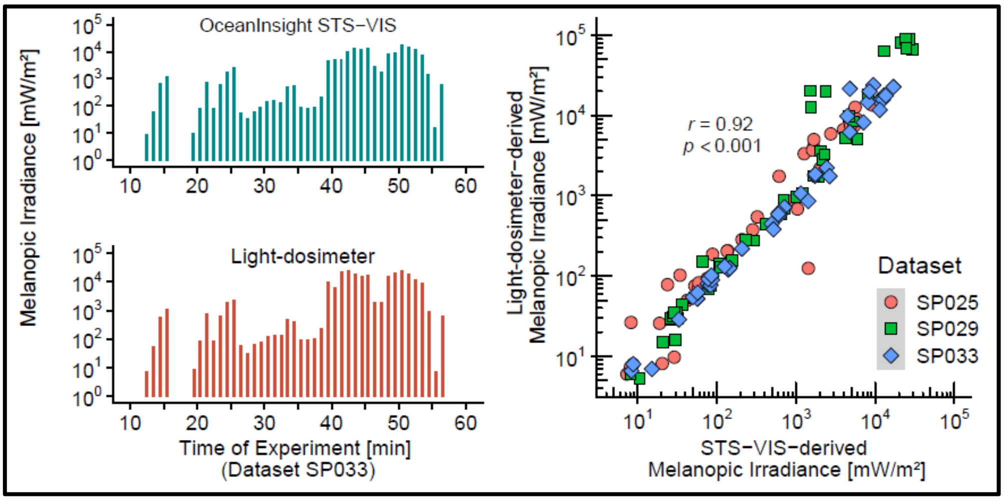

Figure 10 – Comparison of melanopic irradiance levels derived from a spectrometer and a light-dosimeter [This figure is licensed under CC-BY]

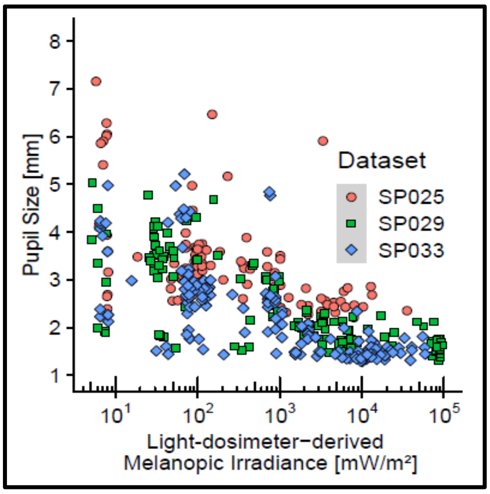

Figure 11 – Relating melanopic irradiance levels derived from a light-dosimeter to physiological responses (pupil diameter) [This figure is licensed under CC-BY]

4 Discussion

The results achieved with the light-dosimeters during the trial period look promising. Findings from the preliminary testing suggest that the light-dosimeters are well suited for conducting research-grade field measurements. However, further deployments are required to attest to the devices' merit. Therefore, we plan to conduct additional tests in laboratory settings and a feasibility and acceptability study over the coming months. Initial observations such as lower than expected indoor light levels measured in the near-corneal plane and negative average tilt angles will be examined in more detail.

Apart from field measurements and ambulatory experiments, measuring devices like the light-dosimeter can handily be used to document experimental study settings. While some of the recommendations for reporting light exposure in studies investigating non-visual responses to light can be covered using a light-dosimeter (Spitschan *et al.*, 2019), other aspects such as spatial distribution of the stimulus still need to be characterised with the help of other devices. In the medium to long term, data gathered with light-dosimeters might help formulate future recommendations for a healthy light exposure or influence discussions about the appropriate field of view in various settings.

A lot of ideas and information on how to enhance a future version of the light-dosimeter and the associated software has been collected. We are confident that the pace of generating new knowledge about non-visual responses to light can be further increased if the research community works more closely together, e.g., by using a standard data format and even share data.

5 Conclusion

Whereas the light-dosimeters are not the panacea for researching the non-visual responses to light, they will provide researchers with much desired, good quality data using the latest standardised metrics to support, enhance or amend previously held beliefs and recommendations. The light-dosimeters will enable researchers to record the light exposure in the near-corneal plane from individuals of different ages, in different settings, from urban and rural areas, from a range of occupations and at different times of the year. This data will help advance the current understanding between an individual's light exposure and the physiological, psychological, and behavioural responses, which will in turn help define recommendations for a "healthy light hygiene" in modern society, including the important role of daylight.

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Author contributions

The team from Lucerne School of Engineering and Architecture, Horw, Switzerland (J.R.S., B.S, C.d.B., R.H., O.S., G.W., Z.C.) led the actual development and manufacturing of the light-dosimeters (www.light-dosimeter.ch). P.B. provided input throughout the project, analysed the light sensor in 2019 and tested several light dosimeters early in 2021. C.C. provided input throughout the project. R.L. and M.S. led the conjoint cross-spectrometer and pupillometric measurements in 2021.

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