Publishable Summary for 22NRM05 MeLiDos
Metrology for wearable light loggers and optical radiation dosimeters

Overview

New standardised metrics for measuring the physiological, non-visual effects of light have been recently introduced in CIE S 026 and wearable light loggers (also known as light dosimeters) have emerged as a way to measure a person's light dose. However, the optical characterisation of these dosimeters remains challenging because of the compromises needed to make them wearable and affordable. This project aims to provide the scientific and industrial communities with the necessary tools (e.g. best practice guides) for the characterisation and use of wearable light loggers.

Need

Daylight affects human physiological activity and regulates many aspects of society (e.g. waking hours, alertness). On the other hand, the invention of electric lighting has led people to spending more time indoors during the day, including working remotely from home, and staying up later in the evening. However, the intensity of artificial light is only a fraction of that of daylight (a half for a cloudy sky, and less than 1 % of a sunny afternoon), while their spectral compositions differ in terms of blue light proportion. This point is of particular importance because of melanopsin, a photo-pigment present in the eye and involved in physiological responses to light but not in direct vision, called Non Image-Forming (NIF) effects. Implications for health and well-being vary from mood and wakefulness to sleep deprivation, including even more severe health problems, such as heart diseases and cancer. While the study of lighting sources can be performed in laboratories under controlled conditions, the light humans receive under actual environmental conditions is very different due to e.g. window placement, reflectance of materials in the surrounding, habits, etc.

Wearable light loggers are currently being used for the measurement of light exposure on humans, as they are wearable and provide light exposure data during the course of a whole day. These light dosimetry time series are then correlated to other factors, such as melatonin levels or heart rate, to investigate the physiological effects. Although they are compact and lightweight, they often have a black-box design where the sensor technology (e.g. filter-based or spectrally resolved), the data processing (e.g. sampling rate, averaging or other data processing, etc.), or both, are unknown, which makes evaluating their performances even harder. It can then lead to inaccuracies, inappropriate metrics or conclusions due to misinterpretation or incomplete data. There are currently no guidelines or standards for the characterisation of light loggers, and the collected data are thus often considered unreliable due to inaccurate device specifications and/or data processing or interpretation (e.g. a user not familiar with the field misinterprets a specification or metric).

In TN002:2014, CIE has identified the need for the photobiological and photometric quantities to be harmonised. With the rapidly evolving field of lighting (future revision of CIE S 025, publication of CIE S 026, introduction of daylighting by EN 17037 and revision of workplace lighting in EN12464-1) and the spread of wearable devices of all kinds, it is important to keep metrology recommendations and guidelines up to date to ensure reliable studies well support health recommendations and policies.

Objectives

The overall aim of the project is to introduce metrology for light dosimeters, and in particular for light loggers designed to respond to the needs raised by CIE S 026 for measuring melanopsin-related metrics. More specifically, this project will deliver the metrics and procedures, as well as guidelines based on use cases, in order to lay the groundwork addressing the normative standards' needs.

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The specific objectives are:

1. To develop and validate new characterisation methods, and define a validated set of quality indices for wearable optical radiation dosimeters, with a focus on ranges relevant to daily life (i.e. UV and visible). Their validation will be performed against lab-based instrumentation for parameters (e.g. wavelength sensitivity, linearity and angular response) in an intercomparison exercise. The quality indices will be based on those defined by ISO and CIE for illuminance meters and luminance meters.
2. To develop data analysis methods to verify and increase the quality of data, as well as to establish the correlation between different datasets to improve reproducibility and make comparisons from different devices more reliable.
3. To analyse use cases for wearable light loggers based on end user needs, and to then produce recommendations based on those needs on i) (meta-)data model and data formats, as well as summary metrics and on ii) the practical use of light loggers, including device placement, compliance and quality control.
4. To evaluate the performance of new portable devices able to measure spatially resolved photobiological quantities and to compare them with spatially averaging devices, to determine relevancy depending on use case. Additionally, to investigate the shortcomings of current devices regarding their use and to investigate the benefits and drawbacks of spatially-resolved devices.
5. To collaborate with CIE Division 2 and Division 6, and the users of the standards they develop to ensure that the outputs of the project are aligned with their needs, including the provision of recommendations in a form that can be incorporated into future standards at the earliest opportunity. Additionally, to promote the results to other relevant parties such as lighting experts, chronobiologists and sleep specialists through various communication channels available to the participants.

Progress beyond the state of the art and results

Development of characterisation methods and quality indices for light loggers and optical/UV radiation dosimeters (Objective 1):

Though it has been known for over two decades that light has a profound effect on human health and wellbeing, only recently has CIE S 026 defined spectral sensitivity functions, quantities, and metrics to quantify the light triggering these effects. The spectral measurement and characterisation of light sources in testing laboratories are usually well understood and the measurement uncertainties are at an acceptable level for current uses. In recent years, various wearable light loggers and UV radiation dosimeters have been developed to enable the measurement of spectrally weighted irradiances and irradiance doses in field experiments, implementing the standard CIE S 026. Since these instruments need to be portable and light weight, their design differs from those typically used in laboratory environments. Moreover, since these instruments are to be used in field experiments and deployed in numbers, the evaluation of their performance needs to be cheap and time-efficient. Traditional methods of providing traceability for example by measuring the spectral responsivity with the narrow band source are thus not suitable. So far, no standardised methods exist to characterise wearable light loggers and UV radiation dosimeters.

This project will build a metrological framework for the characterisation of wearable light loggers, giving methods for their evaluation, validation, and traceability. The developed methods will be validated through an intercomparison, contributing to measurement capabilities at NMIs as well as in industry. Performance indicators, consisting of a set of quality indices, will be developed in order to make it easier for users to assess the performance of a device in terms of e.g. linearity. The project outcomes will be summarised in a publicly available good practice guide (GPG), which will support CIE in the development of standards for the characterisation of wearable light loggers. The overall goal is to provide guidance and methods to stakeholders on how to reliably characterise wearable light loggers.

In collaboration with CIE JTC 20, the project identified 64 different devices used in studies on the physiological effects of visible light, with a wide diversity in technology, wearing position, and with often limited availability. The project identified several devices of interest for characterisation, limiting its choice to devices that allegedly reported metrics related to non-image forming effects. The project's participants are in the midst of acquiring several of these devices for characterisation.

The project also identified 20 devices to measure UV exposure, most of which are discontinued. The core sensor for these solar UV dosimeters is often discontinued too, and characterisation for UV sensors is more tricky. Coupled with less demand due to chemical patch alternatives, solar UV dosimeters are less available on the market. As such, the project will only be able to evaluate 2 models of solar UV dosimeters, and plans to potentially also include a hand-held version of such a device.

Development of data analysis methods for data quality verification and data reproducibility (Objective 2):

The data currently collected by wearable light loggers, are usually affected by multiple factors, for example who is wearing them (i.e. if the device is worn correctly, or at all times, etc.), the indoor/outdoor environment, etc. It is therefore necessary to include processes and data analysis methods to validate the data. This project will provide the necessary guidelines for preparing and carrying out field studies with wearable light loggers in a way that promotes data quality and reliability, with a user-oriented mind-set. This will include data and metadata formats and data validation tools and recommendations to facilitate the reproducibility, data transfer and comparison between data sets. A research-oriented software ecosystem will be included, comprised of various modules for data format conversion, data analysis, validation, and visualisation, as well as a cross-comparison between different devices and studies with harmonised data format.

A software ecosystem is being developed by the project to provide research user with a powerful tool to analyse, validate and visualise their data and results and make them FAIR. The software goes by the name LightLogR and is currently already functional (documentation: https://tscnlab.github.io/LightLogR/, code: https://github.com/tscnlab/LightLogR). More features will be added during the project, in particular concerning data and metadata formats and validation. The project's participants are in contact with several device manufacturers and users to get feedback and ideas on this particular aspect.

The project also collected useful information by interviewing experts who used light loggers in the field. This information will be used to design a set of auxiliary data which will help during the validation and consolidation of the light logging data, granting more confidence in the subsequent analysis.

Meta-data recommendations were put forward by a working group within the Daylight Academy, a stakeholder of the project, in a paper in late 2023 (under review). These recommendations will be further developed and validated through the project.

To analyse use cases for wearable light loggers based on end user needs, and to then produce recommendations based on those needs on i) (meta-)data model and data formats, as well as summary metrics and on ii) the practical use of light logger (Objective 3):

There are multiple applications for wearable light loggers and different devices designed to answer specific applications. For example, a study on the effect of light sensitivity on ASD (Autistic Syndrom Disorder) patients will have different requirements to a study of wall paint colour on wakefulness of office workers, both in terms of device technical specifications and in terms of practical use (e.g. when, how the device is worn, data relevancy, etc.). There are currently no guidelines or recommendations related to the proper selection and use of wearable light loggers. This project will define a usage landscape based on the applications' needs and provide recommendations on the quality indices and other characteristics that a user should pay attention to while choosing and using wearable light loggers.

A survey was carried out with more than 20 experts in the field of chronobiology, health and well-being, in order to understand their experience of light dosimetry, including the purpose of their studies, their use of light loggers, the limitations and problems encountered both on the wearer and scientist side, and several other key information. A summary of the user needs based on these interviews is currently being drafted.

The experience of the scientists with the data was also a key part of the survey. Things such as how the data was validated and analysed, and the confidence the users had in the data was investigated. A draft protocol was designed, incorporating these findings for a field-testing demonstration to be carried out later.

Portable devices performance evaluation for the measurement of spatially resolved photobiological quantities. Comparison with spatially averaging devices and investigation of benefits/drawbacks of spatially-resolved devices (Objective 4):

The fast development of wearable devices and the spread of their use for aggregating data with constellations of devices or for behavioural studies, poses a major challenge for the reliability and traceability of the data generated by these devices. New sensor technologies for wearable light loggers will be investigated in this project in order to ensure the delivered methods and recommendations will remain transferrable to new technologies. In particular, the use of spatially resolved devices will be investigated since the eye is also a spatially resolved sensor and the study of non-visual effects of light should not stop at spatially averaged light levels.

Several sensors were identified with a potential for their incorporation into a spatially-resolved light logger (2D light logger). Most of the devices came in the form of micro-cameras used in various applications such as medical diagnosis, augmented reality, or even sensors from smartphones. The availability and practicality of some of the sensors for custom applications such as this research is questionable, and the project has yet to acquire relevant sensors to start testing the viability of using them in 2D light loggers.

CIE JTC 20 expressed the need for such devices during the CIE quadrennial conference in Ljubjana, in September 2023, with several groups of researchers casting doubt on the relevance of illuminance as a reliable metric for non-visual effects, since the eye does not behave like a cosine-corrected illuminance meter, but like an imaging apparatus. Some research also showed evidence of spatial dependence of non-visual effects of light, with considerations such as pupil size, eyelid position, or even the spatial repartition of the melanopsin-containing cells in the retina.

An investigation into the benefits and drawbacks of 2D light dosimetry was carried out by the project's participants, based on which a questionnaire was prepared and distributed to experts in the field of light dosimetry for their feedback. There are currently around 10 replies, with varying degrees of expertise on the technical aspects of light dosimetry, which points to a need of also raising awareness on the incompleteness of data from spatially-averaging light dosimeters.

Outcomes and impact

The project has so far participated in various international instances of standardisation committees, notably chairing the CIE JTC 20 on 'Wearable alpha-opic dosimetry and light logging methods, limitations, device calibration and data schemes'. At the CIE quadrennial conference in Ljubljana, September 2023, several participants were present and shared the news about the project, its goals, and interacted with potential stakeholders. Several presentations of the project's goals, methods, participants and early results were given, mainly on the national level. Introductory trainings on the use of the software ecosystem were given online to interested parties among stakeholders and the participants' network. A workshop was also organised on light beyond vision. The identity framework of the project was set, with the creation of the website, flyers for events, poster and presentation templates, and the first newsletter was distributed to the stakeholders. All materials from the newsletter to the stakeholder workshop presentations were made available on Zenodo and/or on the project website. Introductions to the subject were made to the general public through the University of San Pablo's science week (for students) and through an article in the general Spanish press.

Outcomes for industrial and other user communities

The project will provide the industrial and scientific communities in the field of wearable light loggers and UV radiation dosimeters with the methods, recommendations, and guidelines as necessary for the characterisation of these devices. The quality indices will not only benefit users as a way to assess the performance of a device but also industry that wants to design improved devices or similar devices that look at other wavelengths.

Improving light dosimetry will also enhance the quality of studies regarding Non-Image Forming (NIF) effects of light and benefit lighting experts, interior architects and similar professions by providing them with useful tools to evaluate their work in situ. As both regulations and public awareness are progressing towards more health considerations in buildings, it will provide opportunities for the lighting industry to improve their products to be more in line with trustful, state of the art research. Light loggers could also be used by these experts, empowering them with new tools to easily monitor the lighting changes throughout a day or with changes in furniture, paint, and other interior arrangements.

Currently, manufacturers have expressed a lot of interest in the characterisation methods for their devices as well as in the data and metadata framework to be developed in the project.

Outcomes for the metrology and scientific communities

The project will deliver recommendations and guidelines for the characterisation and use of wearable light loggers. This will improve the quality and reliability of the data generated by clinical studies, as well as the robustness of their results and conclusions. Researchers and clinical staff will be able to choose devices which best fit their application as well as get more reliable light dosimetry data and therefore, more reliable conclusions in their studies.

Several researchers have developed their own devices because they found commercially available devices unsatisfactory for their needs. They expressed interest in the characterisation methods and proposed a collaboration to include their devices in the development of the methods or the comparison that will follow. Several research scientists were also impressed by the LightLogR software ecosystem, expressing their willingness to either contribute data to further develop the software, or to use it on their own. While work on solar UV radiation dosimeters will not be as extensive in this project, it will still benefit scientists by providing them with more reliable tools to measure UV doses in the field and assess its impacts on human health. Currently, UV doses are generally measured with chemical patches, which are both cheaper, more available on the market, but also provide less reliable, quantitative results. One of the two main issues for UV dosimeters is the fact that the devices are often discontinued, so finding relevant, available devices is a challenge that the project but also the beneficiaries of the project's work will face. This is due to the manufacturers having the same issue with the core sensors in these devices, which are often discontinued. The second main issue is about the difficulty in characterising the device, which is being addressed by the project.

The project will also improve the performance of the wearable light loggers that will be designed for and used by the general public, providing more exhaustive and accurate information about the light dose they receive. Data provided by the general public (in this case light dosimetry data) can be used for Big Data studies. Making this light dosimetry Big Data reliable is again key for the researchers that will use it to make statistical analyses of practices in the general public.

The metrology benefits are more straightforward, as the project will lay the groundwork for normalisation bodies regarding wearable light loggers, with the methods not only limited to wearable light loggers for NIF effects of light, but also including UV radiation dosimeters.

Outcomes for relevant standards

The results of this project will be used to complement CIE S 026, which defines the metrics for NIF effects of light, with recommendations on how these should be properly measured, such as device requirements, characterisation and practical use. The project will also contribute to the implementation of standards in daylighting EN 17037 and workplace lighting in EN12464-1 by improving the reliability of the tools available for building experts to assess their compliance to those standards. As currently there is no European standard on solar UV exposure for outdoor workers, this project should contribute to the development of new standards on solar UV exposure, in particular by providing insights for potential Personal Prevention Equipment (PPE) against solar UV radiation.

The project is working in tandem with CIE JTC 20, with the project being focused more on applications rather than guidelines, providing validated and practical methods for characterising light dosimeters and actually using them in the field. It also expands to solar UV dosimeters and spatially-resolved devices. This collaboration includes cross-checking the state of the art for wearable light loggers and sharing insights into current practices on the characterisations of illuminance meters, the devices most closely related to current technologies of wearable light loggers, which the project's participants are more familiar with.

Longer-term economic, social and environmental impacts

Currently, very little is known about how light exposure affects human health and wellbeing. The introduction of metrology for wearable light loggers will ensure scientists and clinical staff have reliable data to better understand the role of lighting in human health and wellbeing. Chronobiologists and sleep specialists will benefit from having reliable tools to study and understand the effect of light exposure on human physiology. The confidence in scientific results mentioned above will hasten the emergence of efficient guidelines and standards for the lighting field as well as health experts. This in turn will improve the livelihood, wellbeing and productivity of the European and other communities for the long term. The same health benefits are expected for the extended work to UV radiation dosimeters. The emerging increase in UV exposure as a result of global warming is expected to increase the number of skin cancer case, as warmer and sunnier days means more time spent exposed to UV radiation. In view of this, characterisation methods and quality indices for the performance of solar UV dosimeters with the aim of optimising protective measures and effective strategies for skin cancer prevention are of great importance.

Moreover, connected devices for monitoring various parameters are already available to the general public (Internet of Things or IoT) but it is not always known what the data means exactly, both among the general public and sometimes, the manufacturer. Recommendations and future standards for the characterisation of light dosimeters, as well as recommendations for the formatting and use of the data, will improve the understanding of the health implications of light exposure by manufacturers, and in turn by the end user.

Potential future uses and follow-up work

The characterisation methods developed in this project are applicable in a wider frame to other portable light logging devices. This includes devices for monitoring plant growth and health in agriculture for example. The LightLogR framework developed in the project is already being used to compare datasets and validate measurements. The emphasis the participants put on practicality, exhaustivity and methodology will make it easier to both adopt the methods developed, which will enhance reproducibility and comparability for future results. The importance of getting spatially-resolved data is also highlighted by many experts in the field as the eye is an imaging apparatus, and the topic was prominent at the CIE quadrennial conference in Ljubljana for light dosimetry in various situations. The project will keep its contribution closely related to currently used devices in order to keep the consistency that constitutes the core of its effort.

List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 June 2023, 36 months	
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Chief Stakeholder Organisation: Commission Internationale de l'Eclairage (CIE)	Chief Stakeholder Contact: Diana Wernisch, CIE General Secretary	
Internal Beneficiaries: 1. LNE, France 2. Aalto, Finland 3. CMI, Czechia 4. RISE, Sweden 5. TUBITAK, Türkiye 6. VSL, Netherlands	External Beneficiaries: 7. FUSP-CEU, Spain 8. Iberoptics, Spain 9. INEGI, Portugal 10. THUAS, Netherlands 11. TUM, Germany 12. UCM, Spain	Unfunded Beneficiaries: 13. BAuA, Germany
Associated Partners: 14. HSLU, Switzerland 15. METAS, Switzerland 16. SFI Davos, Switzerland		