Measurement 235 (2024) 114909

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Illuminating the future of wearable light metrology: Overview of the MeLiDos Project

Manuel Spitschan [a,b,c,*], Johannes Zauner [a,b], Maria Nilsson Tengelin [d], Constantinos A. Bouroussis [e], Patrik Caspar [e], Fabien Eloi [f], on behalf of the MeLiDos consortium

[a] Max Planck Institute for Biological Cybernetics, Max Planck Research Group Translational Sensory & Circadian Neuroscience, Tübingen, Germany
[b] TUM School of Medicine and Health, Department Health and Sports Sciences, Chronobiology & Health, Technical University of Munich, Munich, Germany
[c] TUM Institute for Advanced Study (TUM-IAS), Technical University of Munich, Garching, Germany
[d] Department of Measurement Science and Technology, RISE Research Institutes of Sweden, Borås, Sweden
[e] Labor Optik, Swiss Federal Institute of Metrology METAS, Bern, Switzerland
[f] Direction de la Métrologie Scientifique et Industrielle, Département Photonique, Laboratoire National de Métrologie et d'Essai (LNE), Paris, France

ABSTRACT

Light exposure profoundly influences human health, regulating circadian rhythms and impacting wakefulness and sleepiness. Estimating the effects of light exposure under everyday conditions requires personal, wearable light logging and dosimetry approaches. This article introduces the MeLiDos Project (2023–2026), supported by the European Association of National Metrology Institutes (EURAMET). The project's first branch defines quality indices and calibration standards for wearable light loggers, adapting existing metrological standards to their smaller size and distinct purpose in the field rather than the laboratory. The second branch develops a software ecosystem, including the open-source R software package *LightLogR*, designed to manage the increasing volume of data, ensuring reusability, accessibility and interoperability of data. The third branch explores the potential of spatially resolved light dosimetry. The MeLiDos Project anticipates advancements in wearable light metrology, paving the way for optimizing human health and well-being through wearable light logging technologies.

1. Introduction

Light is essential for human health, affecting various physiological and behavioral functions [1]. The human circadian clock is synchronized by the environmental light–dark cycle defined by solar radiation and extended due to the availability of electric light sources. Additionally, light affects physiology acutely, leading to the suppression of the endogenous hormone melatonin and increasing alertness [2]. Biologically, these so-called 'non-visual' effects of light are mediated by a set of light-sensitive cells in the retina [3] independent of the three types of cones in the retina (long-wavelength [L], medium-wavelength [M], and short-wavelength [S] cones), which allow us to see color, motion, and spatial detail, and the rods, which give us rudimentary vision under dim-light conditions. The intrinsically photosensitive retinal ganglion cells (ipRGCs), which were only discovered in the late 1990s/early 2000s [4], are sensitive to short-wavelength light (with a peak near 480 nm) due to the photopigment melanopsin. Following the discovery of the melanopsin-containing ipRGCs, the International Commission on Illumination (CIE) developed and published the International Standard CIE S 026/E:2018 in 2018 [5], which describes spectral sensitivity functions and novel quantities and metrics for quantifying the impact of light on humans concerning the non-visual effects of light using a novel metrological system, the α-opic system [6]. The term "α-opic" is a placeholder for one of the five photoreceptor classes in the human retina (e.g. melanopic for the melanopsin-influenced responses).

A large and growing body of literature examines light's impact in the laboratory under well-controlled conditions. Findings from these studies are supported by converging evidence from field and large-scale cohort studies linking light exposure to negative health outcomes. In 2022, the first consensus recommendations for light exposure under everyday conditions were published based on a meta-analysis, proposing upper bounds for light levels in the (pre-)sleep environment and recommending a minimum of light exposure during the day, corresponding to 250 lx of daylight [2]. As research on the non-visual effects of light matures, measurements of light exposure under everyday conditions become key to applying the new neurobiological knowledge base to optimize health outcomes.

* Corresponding author at: TUM School of Medicine and Health, Department Health and Sports Science, Chronobiology & Health, Technical University of Munich, Munich, Germany.

E-mail address: manuel.spitschan@tum.de (M. Spitschan).

https://doi.org/10.1016/j.measurement.2024.114909
Received 18 December 2023; Received in revised form 3 May 2024; Accepted 13 May 2024
Available online 14 May 2024

1.1. Measuring personal light exposure

Laboratory studies, in which light exposure can be manipulated and tightly controlled, have generated a wealth of mechanistic insights, such as dose–response curves for the non-visual effects of light, the underlying spectral sensitivities and characterization of underlying mechanisms [7]. Light exposure under real-world conditions is very different from these laboratory conditions, which are designed to characterize the biological systems under investigation in isolation. Exposure to daylight, distinct in its spectral and spatial properties, varies throughout the day with different solar angles and sky conditions. Light exposure indoors is rarely constant as we move between buildings and rooms and face different directions in a room with different light sources, geometry, and surfaces. Additionally, our head orientation changes and our eyes can move several times a second, resulting in a highly complex light pattern reaching the retina and its photoreceptors [8].

Since the 1980s, researchers have used mobile light loggers worn by participants to capture time-series of personal light exposure [9]. Studies with light loggers have yielded a series of key insights, including striking differences in light exposure between seasons, geographical locations, and the association between light exposure, and health and illness. From the earliest studies in the early 1980s [10,11], the literature shows patterns of low personal light exposure levels during the day and high levels at night, compared to natural outdoor light availability. Several key findings relating light exposure to health include the association between light exposure and metabolic phenotype [12], daytime sleepiness and alertness [13,14], psychiatric illness [15], and ocular health, specifically myopia.

Technologically, light loggers exist in different form factors and have different technical and optical capabilities, and not all light logging devices measure the same thing and provide the same metrics. The growing market of light loggers necessitates clarity on the abilities and limitations of wearable light logging. The new MeLiDos Project (22NRM05 Metrology for wearable light loggers and optical radiation dosimeters; project website https://melidos.eu/; Zenodo collection: https://zenodo.org/communities/22nrm05_melidos/about), supported by the European Association of National Metrology Institutes (EURAMET), is addressing these questions in a consortium bringing together 16 institutions across ten countries (Czechia, Finland, France, Germany, Netherlands, Portugal, Spain, Sweden, Switzerland, Turkey; see Table 1). The MeLiDos Project is closely linked to the Joint Technical Committee within the International Commission on Illumination (CIE), JTC20 – *Wearable alpha-opic dosimetry and light logging methods, limitations, device calibration and data schemes*, which will write a Technical Report on characterization and calibration of wearable light loggers.

Table 1
Member institutions of the MeLiDos Consortium (in alphabetical order).

Institution	Country
Aalto University, Metrology Research Institute	Finland
Bundesanstalt für Arbeitsschutz und Arbeitsmedizin / Federal Institute for Occupational Safety and Health (BAuA)	Germany
Český Metrologický Institut / Czech Metrology Institute (CMI)	Czech Republic
De Haagse Hogeschool / The Hague University of Applied Sciences (THUAS)	Netherlands
Fundación Universitaria San Pablo CEU	Spain
Hochschule Luzern / Lucerne University of Applied Sciences and Arts (HSLU)	Switzerland
Iberoptics Sistemas Ópticos, S.L.	Spain
INEGI – Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial	Portugal
Laboratoire national de métrologie et d'essais (LNE)	France
Physikalisch-Meteorologisches Observatorium Davos / World Radiation Center (PMOD/WRC)	Switzerland
RISE Research Institutes of Sweden AB (RISE)	Sweden
Swiss Federal Institute of Metrology METAS	Switzerland
Technische Universität München / Technical University of Munich (TUM)	Germany
TÜBİTAK Ulusal Metroloji Enstitüsü (UME)	Turkey
Universidad Complutense de Madrid	Spain
VSL National Metrology Institute (VSL)	Netherlands

2. Towards novel approaches in personal light logging

The MeLiDos Project includes three lines of work, covering metrology (Work Package 1), tooling (Work Package 2), and spatially resolved light logging (Work Package 3) (see Fig. 1).

2.1. Work Package 1: Metrology for personal light loggers

To be wearable and fit for everyday use, light loggers' manufacturing and optical requirements differ from typical measurement devices used in the laboratory and field. The components are necessarily smaller and more lightweight, and design decisions often add additional constraints. This may lead to suboptimalmelidos optical performance properties compared to devices larger in size and scale optimized for precise measurements [16]. Notably, most wearable light loggers are not just measuring light; they are typically measuring it for the express purpose of relating it to the physiological and behavioral response to light and, by extension, to health and wellbeing. To ensure high-quality measurements, definitions of target performance characteristics and guidelines for capturing these are needed [17,18]. The first branch of the MeLiDos Project aims to define a set of quality indices and suggest comprehensive and calibration standards. While the primary focus of the MeLiDos Project will be on light loggers capturing α-opic information in the visible spectrum, the project will also examine state-of-the-art personal UV dosimeters from a characterization and calibration perspective.

2.2. Work Package 2: Light logging toolbox

As the field of light logging develops and more light loggers capturing α-opic information appear on the market [19–21], a growing body of data will be collected using a variety of commercially available or research-grade light loggers. These differ in their form factors, wearing locations, optical performance characteristics, outputs and data formats. Given the growing interest in understanding the impact of light on human health, a 'data deluge' may be anticipated in the next few years. Additionally, many potential metrics for summarizing time series of light exposure are available, with no scientific consensus on which are relevant for health outcomes [9]. A common framework for working with light logging data is currently lacking [22], leading to a fragmented research landscape and low comparability between studies.

To process the data and make it findable, accessible, interoperable and reusable (FAIR; [23]), principled approaches for data collection, processing, and storage are needed. In the second branch of the MeLiDos Project, a software ecosystem will be developed for processing and analyzing data, and perform housekeeping and data-wrangling tasks, including validation methods for confirming data and metadata integrity. A core component will be a novel open-source (GPL v3.0) software package termed LightLogR [24] (website: https://tscnlab.github.io/LightLogR/, source code: https://github.com/tscnlab/LightLogR/), which facilitates the analysis of wearable light logger data. Given the diversity of wearable light loggers on the market, we will also examine how to make them usable for various end users [25]. Furthermore, we will collect the first global cohort dataset of personal light exposure using a harmonized data collection protocol [26].

2.3. Work package 3: Towards spatially resolved light logging

Historically, personal light logging has focused on measuring illuminance, thereby enforcing a cosine weighting on the light's angle of incidence. While this is an established method and a convenient simplification, it does not adequately reflect that the human eye differs

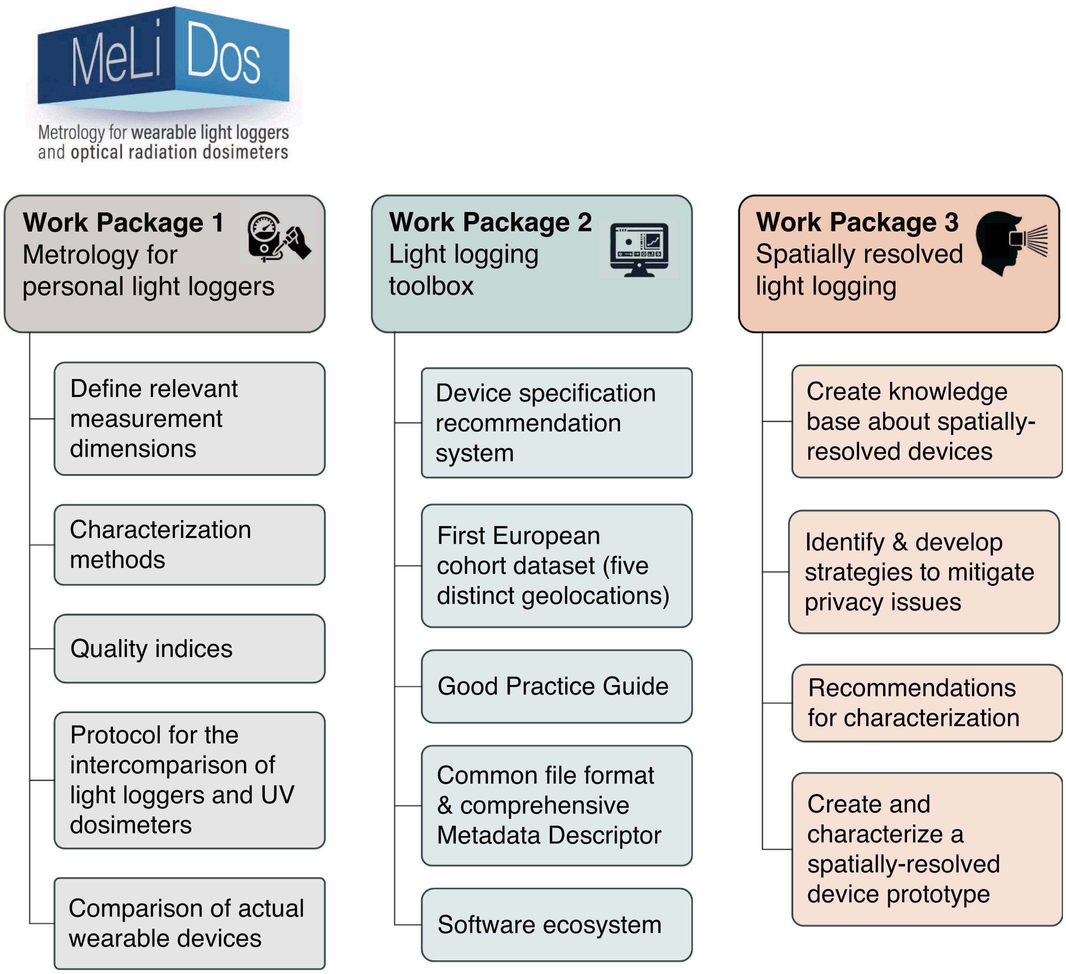

Fig. 1. Overview of the MeLiDos Project and its expected primary outcomes.

from a cosine-corrected detector [27,28]. The ipRGCs are distributed anisotropically, peaking in their density, not in the most central spot where our vision is sharpest – the fovea – but a few millimeters to the side. Laboratory studies have identified asymmetries in the effect of light is depending on which part of our visual field is illuminated [29–32]. This information is lost when using cosine-corrected or spatially averaging light loggers. Furthermore, certain sections of a standardized hemispherical irradiance measurement are outside the field of view (FOV) of the eye due to, e.g., eyelid position, leading to considerable variance in the amount of light that can reach the retina, depending on the configuration of light sources within the FOV [33].

The third and last branch of MeLiDos is investigating the technical feasibility of spatially resolved light dosimetry. This may be accomplished through calibrated miniaturised imaging sensors combined with special optics for capturing light exposure from different directions and different spectral bands. Given that the spectral sensitivities of the ipRGCs are different from those of the cones – which underlie our color vision and have spectral sensitivities that can be linearly transformed to RGB spectral sensitivities in conventional RGB sensors – specialized calibration approaches are needed. In addition, the feasibility of low-resolution multispectral imaging solutions will be investigated. In this case, more precise spectral information can be gathered.

As spatially resolved light loggers can capture personal information – such as faces of individuals in the wearer's point of view – spatially resolved light logging poses a special concern in terms of privacy, ethical and legal aspects, which do not arise in conventional, spatially averaging light loggers. The MeLiDos Project will explore novel approaches to mitigate real and perceived data privacy concerns. One such approach may lie in ensuring that imaging data will not be retained or used beyond calculating the relevant quantities and metrics, or using computer-vision and machine-learning techniques for the detection and discarding of privacy-sensitive information.

3. Generating impact through stakeholder engagement and standardization

A key component of the future of wearable light logging lies in developing and establishing robust standards around characterization and calibration, and harmonizing data and metadata formats to maximize interoperability and thereby utility of the data. To this end, the CIE JTC20 works closely with the MeLiDos Consortium, ultimately leading to a CIE Technical Report. Many consortium members are also members of other national and international standardization committees and work groups related to indoor lighting and other fields for which light logging devices can become helpful and are actively collecting the needs for measurements expressed in those groups.

Another critical component is the engagement of diverse stakeholders in developing sensible and scalable methodologies for characterizing and using light loggers. In the first stakeholder workshop, which took place in November 2023, the MeLiDos Consortium introduced the project and captured the interest of global researchers and device manufacturers. To maximize communication and dissemination, the MeLiDos Consortium will continue engaging with the communities interested in using light logging devices. Once the first results emerge from the MeLiDos Project, a program of workshops and training events is planned.

4. Conclusion

Wearable light logging is an emerging technique with great technological, clinical, and scientific potential. We have described three critical areas of research and development addressed in the MeLiDos Project: metrology for light loggers, tooling and techniques for light logging, and spatially resolved light logging. The next few years will yield critical developments in these areas to improve the measurement of personal light exposure, sparking and aiding new research to optimally support human health and well-being.

Funding statement

The project (22NRM05 MeLiDos) has received funding from the European Partnership on Metrology, co-financed by the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

CRediT authorship contribution statement

Manuel Spitschan: Writing – review & editing, Writing – original draft, Conceptualization. **Johannes Zauner:** Writing – review & editing, Visualization. **Maria Nilsson Tengelin:** Writing – review & editing, Conceptualization. **Constantinos A. Bouroussis:** Writing – review & editing. **Patrik Caspar:** Writing – review & editing, Conceptualization. **Fabien Eloi:** Writing – review & editing, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data were used for the research described in the article.

References

[1] C. Blume, C. Garbazza, M. Spitschan, Effects of light on human circadian rhythms, sleep and mood, Somnologie 23 (3) (2019) 147–156.
[2] T.M. Brown, et al., Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults, PLoS Biol 20 (3) (2022) e3001571.
[3] R.J. Lucas, et al., Measuring and using light in the melanopsin age, Trends Neurosci 37 (1) (2014) 1–9.
[4] I. Provencio, et al., A novel human opsin in the inner retina, J Neurosci 20 (2) (2000) 600–605.
[5] CIE S CIE, 026/E:2018: CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light, CIE Central Bureau, Vienna, Austria. https://doi.org/10.25039/S026.2018.
[6] L.L.A. Price, P. Blattner, Circadian and visual photometry, Prog Brain Res 273 (1) (2022) 1–11.
[7] T.M. Brown, Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions, J Pineal Res 69 (1) (2020) e12655.
[8] M. Spitschan, Time-varying light exposure in chronobiology and sleep research experiments, Front Neurol 12 (2021) 654158.
[9] S.L. Hartmeyer, M. Andersen, Towards a framework for light-dosimetry studies: Quantification metrics, Light Res Tech (2023), https://doi.org/10.1177/14771535231170500.
[10] N. Okudaira, D.F. Kripke, J.B. Webster, Naturalistic studies of human light exposure, Am J Physiol 245 (4) (1983) R613–R615.
[11] T.J. Savides, et al., Natural light exposure of young adults, Physiol Behav 38 (4) (1986) 571–574.
[12] K.J. Reid, et al., Timing and intensity of light correlate with body weight in adults, PLoS One 9 (4) (2014) e92251.
[13] R. Lok, et al., Timing of outdoor light exposure is associated with sleep-wake consolidation in community-dwelling older men, Front Sleep 2 (2023), https://doi.org/10.3389/frsle.2023.1268379.
[14] A. Didikoglu, et al., Associations between light exposure and sleep timing and sleepiness while awake in a sample of UK adults in everyday life, Proc Natl Acad Sci U S A 120 (42) (2023), https://doi.org/10.1073/pnas.2301608120 e2301608120.
[15] A.C. Burns, et al., Day and night light exposure are associated with psychiatric disorders: an objective light study in >85,000 people, Nature Mental Health 1 (11) (2023) 853–862.
[16] L.L. Price, A. Lyachev, M. Khazova, Optical performance characterization of light-logging actigraphy dosimeters, J Opt Soc Am A Opt Image Sci Vis 34 (4) (2017) 545–557.
[17] M. Spitschan, et al., Verification, analytical validation and clinical validation (V3) of wearable dosimeters and light loggers, Digit Health 8 (2022), https://doi.org/10.1177/20552076221144858, 20552076221144858.
[18] J. van Duijnhoven, et al., Recommendations for measuring non-image-forming effects of light: A practical method to apply on cognitive impaired and unaffected participants, Technol Health Care 25 (2) (2017) 171–186.
[19] A. Mohamed, et al., Wearable light spectral sensor optimized for measuring daily alpha-opic light exposure, Opt Express 29 (17) (2021) 27612–27627.
[20] N. Mohammadian, et al., A wrist-worn Internet of Things sensor node for wearable equivalent daylight illuminance monitoring, IEEE Internet Things J 11 (9) (2024) 16148–16157, https://doi.org/10.1109/JIOT.2024.3355330.
[21] J.R. Stampfli, et al., The Light-Dosimeter: A new device to help advance research on the non-visual responses to light, Light Res Technol 55 (4–5) (2023) 474–486.
[22] S.L. Hartmeyer, F.S. Webler, M. Andersen, Towards a framework for light-dosimetry studies: Methodological considerations, Light Res Tech 55 (4–5) (2022) 377–399, https://doi.org/10.1177/14771535221103258.
[23] M.D. Wilkinson, et al., The FAIR Guiding Principles for scientific data management and stewardship, Sci Data 3 (2016) 160018.
[24] J. Zauner, S.L. Hartmeyer, M. Spitschan, LightLogR: Working With Wearable Light Logger Data. R Package, 2023.
[25] E. Balajadia, et al., Usability and acceptability of a corneal-plane alpha-opic light logger in a 24-h field trial, Digit Biomark 7 (1) (2023) 139–149.
[26] C. Guidolin, et al., Protocol for a prospective, multi-centric, cross-sectional cohort study to assess personal light exposure, medRxiv, 2024, https://doi.org/10.1101/2024.02.11.24302663.
[27] D.H. Sliney, How light reaches the eye and its components, Int J Toxicol 21 (6) (2002) 501–509.
[28] D.H. Sliney, Exposure geometry and spectral environment determine photobiological effects on the human eye, Photochem Photobiol 81 (3) (2005) 483–489.
[29] M. Ruger, et al., Nasal versus temporal illumination of the human retina: effects on core body temperature, melatonin, and circadian phase, J Biol Rhythms 20 (1) (2005) 60–70.
[30] E.K. Visser, D.G. Beersma, S. Daan, Melatonin suppression by light in humans is maximal when the nasal part of the retina is illuminated, J Biol Rhythms 14 (2) (1999) 116–121.
[31] G. Glickman, et al., Inferior retinal light exposure is more effective than superior retinal exposure in suppressing melatonin in humans, J Biol Rhythms 18 (1) (2003) 71–79.
[32] M.S. Rea, R. Nagare, M.G. Figueiro, Relative light sensitivities of four retinal hemi-fields for suppressing the synthesis of melatonin at night, Neurobiol Sleep Circadian Rhythms 10 (2021) 100066.
[33] J. Zauner, K. Broszio, K. Bieske, Influence of the human field of view on visual and non-visual quantities in indoor environments, Clocks Sleep 5 (3) (2023) 476–498.