Final Public Report for 22NRM05 MeLiDos
Metrology for wearable light loggers and optical radiation dosimeters

Overview

The introduction of standardised metrics for the non-visual effects of light created a need for reliable measurements of personal light exposure. This project developed and validated methods, quality indices, guidance and software tools for wearable light loggers and solar UV dosimeters, improving the accuracy, reliability and reproducibility of field measurements. It also established harmonised protocols for data collection and analysis and delivered what is likely the first multinational dataset of personal light exposure using a common methodology. The results provide researchers, manufacturers and standardisation bodies with a stronger foundation for future research, standards development and evidence-based health policies.

Need

Daylight has historically regulated many aspects of human physiology and societal activity. Since the widespread adoption of electric lighting people spend more time indoors during the day and remain active for longer in the evening. Light influences physiological processes such as circadian regulation, alertness, and hormonal activity through the stimulation of melanopsin, a photopigment in the eye that is particularly sensitive to blue light. Consequently, light exposure has implications for health outcomes ranging from mood and sleep quality to more severe health problems, such as heart diseases and cancer.

Researchers investigating these relationships need reliable measurements of the light exposures of individuals in their daily lives. While laboratory studies provide valuable information under controlled conditions, real-world light exposure is more complex and depends on e.g., window placement, reflectance of materials in the surroundings, personal activities and behavioural patterns. Compact, light-weight wearable loggers offer a practical way to collect data that can be related to physiological and health indicators in a moderately invasive way. However, differences in sensor technology, data processing methods, and device performance hindered evaluation of measurement quality and comparison of results between studies. The lack of harmonised procedures for characterising wearable light loggers and solar UV dosimeters reduced confidence in the accuracy, traceability, and reproducibility of the collected data.

These needs became more urgent following the publication of CIE TN002:2014 and CIE S026:2018, together with developments in standards related to daylighting (EN 17037) and workplace lighting (EN 12464-1). Researchers, manufacturers and standardisation bodies needed improved measurement capabilities and clear guidance to support reliable studies, facilitate comparison of results, and strengthen the scientific evidence for future recommendations, standards, and health policies. Similar needs also existed for wearable solar UV dosimeters, where reliable measurements of personal UV exposure are needed to support research and occupational health applications.

Objectives

The overall goal of the project was to introduce metrology for personal light radiation dosimeters, particularly for devices designed to respond to the needs raised by CIE S026:2018 for measuring melanopsin-related metrics, but also for solar UV radiation dosimeters. The project aimed to deliver guidelines specifically based on use cases, for both characterisation and field use, to lay the groundwork addressing the normative standards' needs and ensure the reliability and reproducibility of light exposure studies that supports health policy making.

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PU – Public, fully open

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The specific objectives were:

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

Characterisation methods for wearable light loggers and solar UV radiation dosimeters (Objective 1):

In recent years, driven by the publication of the standard CIE S026 for quantifying non-visual effects of light, various wearable light loggers have been developed to measure spectrally weighted irradiances in field experiments. Reliability issues with chemical patches traditionally used to monitor solar UV doses have likewise led to the development of solar UV dosimeters. Wearable devices are designed to be deployed in large numbers, making cost- and time-efficient performance evaluation essential. As they generate time series data rather than direct readings like laboratory instruments, traditional traceability methods are unsuitable and so far, no standardised methods exist to characterise such devices.

In collaboration with CIE JTC 20, more than 64 device models used in studies on the physiological effects of light were identified. Among available devices reporting melanopic equivalent daylight illuminance (mel-EDI), four models were acquired for evaluation. The project also identified more than 20 devices to measure solar UV exposure, most of which had been discontinued. Collaboration with three manufacturers enabled the acquisition of three solar UV dosimeter models.

Following extensive characterisation of the devices, the project developed methods tailored to wearable devices and classified the parameters according to their expected impact in field use and the cost- and time-efficiency of the methods. The results demonstrated that environmental factors (temperature, humidity, polarisation) have little influence on the results compared to the variability expected in field use. New performance metrics were developed as the project identified limitations in current methods, including the relevance of angular dependence measurements for devices designed to mimic the human field of view, and the need for dedicated metrics for low light performance. Verification methods based on broadband sources were proposed to complement time-consuming monochromator-based spectral responsivity measurements, significantly improving testing efficiency. The methods were validated through an intercomparison exercise.

The results provide harmonised guidance for the characterisation of wearable light loggers and solar UV dosimeters and establish a validated set of quality indices adapted to their intended use. The methods and recommendations were published in a publicly available good practice guide and shared with the CIE to support future international standardisation activities.

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

Data collected by wearable light loggers are affected by multiple factors, for example by the wearer (e.g. if the device is worn correctly, or at all times) or the indoor/outdoor environment. For this reason, it is necessary to include data validation processes and methods. This project developed and tested recommendations for conducting field studies with wearable light loggers in a way that promotes data quality, reliability and reproducibility, with a user-oriented research mindset. The work included the development of data and metadata formats, data validation tools, and recommendations to facilitate data transfer, comparison and reproducibility across datasets.

A key outcome was the development of LightLogR (https://github.com/tscnlab/LightLogR), an open-access, research-oriented software ecosystem, providing researchers with a powerful tool to analyse, validate and visualise data, and make the results FAIR (Findable, Accessible, Interoperable, Reproducible). Through active engagement with manufacturers, researchers and other stakeholders, additional features were incorporated during the project, extending the functionality and promoting its adoption within the community. The project progressed beyond the state of the art by providing a comprehensive, openly available framework for validation, visualisation and comparison of wearable light exposure datasets across different devices and studies. New capabilities include data and metadata format verifiers and a novel visualisation method for zero-inflated data sets, enabling more nuanced analysis of very low light level data.

To further improve reproducibility and interoperability, project participants, together with a Daylight Academy working group (a project stakeholder), put forward meta-data recommendations in a paper published in 2024 (https://bmcdigitalhealth.biomedcentral.com/articles/10.1186/s44247-024-00113-9). These recommendations were consolidated with the project's field data collection and analysis, also identifying points of improvement for the developed protocol and auxiliary tools.

To analyse use cases for wearable light loggers based on end user needs and produce recommendations based on those needs on data formats, summary metrics and practical use of light logger (Objective 3):

Wearable light loggers are increasingly used across a wide range of applications. However, despite the growing availability of devices tailored to different use-cases, there are currently no widely accepted guidelines to support the selection, deployment, analysis, or interpretation of wearable light logger data.

To address this gap, the project conducted a survey with more than 20 experts in the field of chronobiology, health and well-being. Information was collected regarding the purpose of light dosimetry measurements, hands-on experience, issues encountered, wearer comments, data validation procedures, analytical approaches, and researchers' confidence in the resulting datasets. The findings were synthesised into a published summary of user needs and incorporated into a protocol and auxiliary tools as well as questionnaires for field data collection. This survey also provided useful insight towards objective 2.

Building on this work, a paper detailing the protocol and data collection to be carried out by the project was published in November 2024. The field data collection campaign was conducted from October 2024 to summer 2025 across seven participating sites, including three collaborators from outside Europe who adopted the same process (protocol, ethics requirements, etc.). In addition, two datasets were contributed from independent studies. As a result, the project implemented what is likely the first multinational personal light exposure measurement campaign using a harmonised protocol. The final dataset comprises 191 adults from nine sites and 1,480 participant-days of combined wearable and experience data. The analysis shows that biologically relevant light exposure is strongly shaped by daily context, outdoor activity, daylight access, and micro-environment, often falling below recommended daytime melanopic levels. The project provides a large-scale multi-country assessment of real-world light exposure at near-corneal level and establishes personal light exposure as a modifiable target for circadian, sleep, and neurobehavioural health. Based on the survey and hands-on experience from field measurements, the project designed a complete guide for the use of wearable light loggers, covering the full workflow from device selection to data analysis.

Investigations into spatially-resolved wearable light loggers (Objective 4):

Emerging evidence suggests that the non-visual effects of light depend on its spatial distribution across the visual field, creating a need for wearable, spatially-resolved light loggers (2D light loggers). To address this need, the project developed and characterised three low-resolution 2D light logger prototypes employing different design approaches. Although not all prototypes are yet fully wearable, each demonstrates distinct advantages and provides a foundation for future device development. The work was documented in a technical

report, and one design is being considered for patenting. Other results will be relevant for imaging devices, both for light dosimetry and other applications

To support this development, several candidate sensors were identified and evaluated, including micro-cameras used in various applications such as medical diagnosis, augmented reality, or even sensors for smartphone applications. The project acquired a range of sensors and assessed their suitability for integration into wearable 2D light loggers. Characterisation requirements were defined based on CIE 244:2021 and the project's work under objective 1.

The project also evaluated the potential benefits and drawbacks of 2D light dosimetry through a questionnaire. Although responses were limited, the result points to a need to raise awareness on the incompleteness of data from current light dosimeters. Spatially averaged measurements do not fully represent the visual input reaching the eye, a need also expressed at the meeting of CIE JTC 20 during the CIE Quadrennial Conference in Ljubljana (September 2023). This idea has yet to become widely spread and is, as of now, only being considered by eye and vision specialists. An interview with a researcher who developed an open-source 2D light logger, the only commercially available device of its kind at the time, helped identify several key characteristics for a functioning research-grade system. In parallel, privacy and regulatory considerations associated with image-capturing devices in public space were assessed, leading to the identification of mitigation strategies, including limiting image resolution.

All objectives were met.

Outcomes and impact

Key dissemination and communication activities

The project actively engaged with the scientific, metrology, and standardisation communities. Results were presented at five international standardisation committee meetings, including CIE JTC 20 on *Wearable alpha-opic dosimetry and light logging methods, limitations, device calibration and data schemes.* The project was also promoted at the CIE Quadrennial Conference (Ljubljana, September 2023) and midterm conference (Vienna, July 2025), where consortium participants presented project-related developments and engaged with researchers and stakeholders. Several members of the consortium also participated in the BIPM event marking the 100th anniversary of V(λ), where various aspects of light-human interaction were discussed, including non-visual effects.

The consortium delivered approximately 30 presentations on the project's objectives, methods, and results at national and international events. Particular interest was generated by the project's data collection protocol and software tools, leading to discussions and proposals for collaboration. Online training sessions on the software ecosystem were provided to interested stakeholders and professional networks, some of which quickly adopted LightLogR. The solar UV dosimetry community also expressed interest in potential future extensions of the software.

Two workshops on the non-visual effects of light were organised for stakeholders and researchers. Consortium's outreach activities targeted the general public through presentations during the FUSP-CEU's science week and coverage in the Spanish press. An article outlining the project's objectives and challenges was published in the journal *Measurement* in 2024.

Outcomes for industrial and other user communities

The project delivered the first harmonised guidance for the characterisation of wearable light loggers and solar UV dosimeters, providing manufacturers, research users and testing facilities with practical and cost-effective methods to evaluate device performance, compare products and demonstrate measurement quality. The methods provide manufacturers with a practical pathway to reduce development and validation costs, improve product reliability and facilitate the introduction of new wearable devices targeting circadian health, occupational health and UV exposure applications. The guide has been published openly and can be directly used by manufacturers, researchers and testing laboratories.

Strong interest in both the characterisation methods and the proposed data and metadata frameworks was expressed by manufacturers throughout the project, which further showed the need for harmonised approaches to device evaluation, data interoperability and quality assurance across the sector.

For occupational health institutions, public-health agencies and clinical researchers, the project improves the confidence in measurements of personal light and solar UV exposure through validated characterisation

methods, quality indices and practical recommendations for field deployment. The resulting increase in reliability and reproducibility enables more robust studies of non-visual effects of light, shift work, sleep disorders, mental health, well-being and UV-related health risks.

The project's researcher guide, harmonised measurement protocol and supporting software tools simplify the collection and analysis of personal light exposure data. These outputs lower the barriers to the adoption of wearable light dosimetry in clinical and epidemiological studies and support its future translation into healthcare applications where light exposure may be used as an indicator or intervention for sleep, circadian and mental-health outcomes.

The open-source LightLogR ecosystem has already gained interest from researchers and stakeholder communities through training activities and collaborative developments during the project. The software constitutes a sustainable pathway for continued uptake of project results beyond the project lifetime and facilitates integration of data from different devices and manufacturers.

Outcomes for the metrology and scientific communities

The project established practical and validated characterisation methods for wearable light loggers and solar UV dosimeters, addressing a significant gap in measurement traceability for wearable optical radiation instruments. The methods provide a common framework for assessing spectral responsivity, angular response, linearity and other key performance parameters, enabling more consistent evaluation between laboratories and devices. The measurements also showcased how several parameters, mainly environmental ones such as temperature, humidity and polarisation, are unlikely to significantly affect device readings in the field as compared to simple wearer behavioural habits and situational variability in the field. The comparison exercise led to further findings about the limitations of current standards and quality indices when applied to wearable light loggers and solar UV dosimeters, as well as highlighted the general direction for further improving the methods developed within the project.

The project's software ecosystem provides openly accessible tools for data validation, visualisation, quality assurance and interoperability. By supporting FAIR data principles and common metadata structures, the project has created infrastructure that will continue to support reproducible research and cross-study comparisons after the end of the project.

The multinational field study represents the largest harmonised dataset generated within the project. As most participants wore sensors in three different positions, on the wrist, chest, and near the eye, the dataset provides a unique opportunity to evaluate the influence of sensor placement on recorded light exposure at an unprecedented scale. Beyond this methodological value, the dataset constitutes a unique resource for investigating real-world light exposure and its relationship to human health and behaviour. It also establishes a valuable baseline for future international studies in this field. The addition of 3 collaborators to this field study and the several proposals for further collaborations exemplify perfectly how a harmonised, reproducible method promotes advances in science.

The project also advanced research into spatially resolved wearable light dosimetry through prototype development and a potential patent application. This work establishes a foundation for future research and potential commercialisation of next-generation dosimeters capable of providing more biologically relevant measurements of light exposure.

Outcomes for relevant standards

By improving measurement traceability, comparability and reproducibility, the project enables standards committees and regulatory stakeholders to evaluate the suitability of current metrics and recommendations using evidence generated from comparable datasets. This is particularly important for the future development of standards and guidance related to non-visual effects of light, daylight exposure, occupational lighting and personal UV exposure.

The project was closely aligned with the needs of CIE JTC 20 on wearable alpha-optic dosimetry and light logging methods and is one of its main contributors. JTC 20 will deliver recommendations in a form suitable for consideration in future standardisation activities. The results were shared by NMIs to their respective national lighting standardisation committees. The project provides the first validated framework for the characterisation of wearable light loggers and solar UV dosimeters and therefore addresses a key gap between established photometric standards and emerging wearable technologies. Project results were provided to CIE Division 2 (measurement) and Division 6 (photobiology) for inclusion in future standards. The EURAMET

TC-PR was updated on the progress and results of the project yearly, with a last presentation planned for January 2027. Guidelines were also provided for data and metadata formats, which can also integrate into standards.

Longer-term economic, social and environmental impacts

In the longer term, the project is expected to support the development of innovative wearable instruments and related services addressing circadian health, sleep quality, well-being and occupational exposure monitoring.

The two guidelines for characterisation and use of wearable light loggers are expected to generate up to 100 000€ of economic turnover for the participants and stakeholders, mainly by saving time and promoting collaborations through enhanced reproducibility and comparability. Improved confidence in measurements is expected to accelerate market adoption of wearable light measurement technologies and reduce duplication of research effort through greater interoperability and comparability between devices. The harmonised measurement protocol, multinational field campaign and resulting dataset demonstrate the feasibility of collecting comparable light-exposure data across multiple countries and organisations using common methodology. This provides a model for future international studies and collaborative research infrastructures.

The LightLogR software ecosystem is expected to generate at least 1 M€ of economic turnover. It provides easily accessible tools for specialists and non-specialists alike, for the data analysis of light logging data, with a FAIR approach. It already received an investment of around 50 000€ from Reality Labs for further development. It can complement manufacturer software, saving time for both researchers and manufacturers, while promoting comparability.

Social impacts are anticipated through improved understanding of how light exposure affects human health, behaviour and well-being. The project provides tools and evidence that may contribute to future health recommendations, workplace practices and building design strategies aimed at improving sleep, alertness, productivity and quality of life.

By enabling more reliable assessment of daylight exposure and lighting conditions in real environments, the project provides evidence that can support daylight-oriented design strategies and more effective use of natural light in buildings, contributing to energy-efficient lighting practices.

The project's results represent a scientific milestone for a better, more systematic understanding on the effects of light and solar UV radiation on health and well-being through more reliable measurement, reproducible and comparable measurements. The project's results are already used and will be used widely to improve light dose measurement practices, and has already contributed to several collaborations and ideas for future research.

List of publications

Guidolin, C. et al (2024) 'Protocol for a prospective, multicentre, cross-sectional cohort study to assess personal light exposure', *BMC Public Health*, 24(1). Available at https://doi.org/10.1186/s12889-024-20206-4

Spitschan, M. et al (2024) 'Illuminating the future of wearable light metrology: Overview of the MeLiDos Project', *Measurement*, 235 p. 114909. Available at https://doi.org/10.1016/j.measurement.2024.114909

Spitschan, M. et al (2024) 'Metadata recommendations for light logging and dosimetry datasets', *BMC Digital Health*, 2(1). Available at https://doi.org/10.1186/s44247-024-00113-9

Spitschan, M. et al (2026) 'Ocular light and optical radiation exposure as a modifiable environmental determinant of health: expert consensus on research gaps and priorities', *BMC Medicine*, 24(1). Available at https://doi.org/10.1186/s12916-025-04608-8

Zauner, J. et al (2026) 'Auxiliary data, quality assurance and quality control for wearable light loggers and optical radiation dosimeters', *npj Biological Timing and Sleep*, 3(1). Available at https://doi.org/10.1038/s44323-025-00067-9

Zauner, J., Biller, A., Spitschan, M. (2025) 'Impact of light logger and dosimeter placement on wearability and appeal in real-life settings', *Open Research Europe*, 5 p. 293. Available at https://doi.org/10.12688/openreseurope.20985.1

Zauner, J., Guidolin, C., Spitschan, M. (2025) 'How to Deal With Darkness: Modeling and Visualization of Zero-Inflated Personal Light Exposure Data on a Logarithmic Scale', *Journal of Biological Rhythms*, 40(5) p. 480-490. Available at https://doi.org/10.1177/07487304251336624

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

List of technical deliverables and the data management plan

Deliverable number	Title	Confidentiality status	Clickable links to 'Public' documents
D1	Research paper on the developed characterisation methods for wearable light loggers (optical radiation dosimeters)	PU - Public, fully open	https://doi.org/10.5281/zenodo.23079430
D2	Good Practice Guide on the characterisation methods of wearable light loggers and solar UV dosimeters	PU - Public, fully open	https://doi.org/10.5281/zenodo.21621071
D3	Comparison report on the interlaboratory comparison of wearable light loggers and solar UV dosimeters	PU - Public, fully open	https://doi.org/10.5281/zenodo.21707083
D4	Summary report on multi-site light dosimetry data set, highlighting through data analysis the quality of the developed methods and tools for validation, correlation and reproducibility	PU - Public, fully open	https://doi.org/10.5281/zenodo.21621179
D5	Good Practice Guide and checklist for light dosimetry field trials, including recommended data and meta-data formats, summary metrics and practical use considerations (device placement, compliance, etc.) with respect to different use cases	PU - Public, fully open	https://doi.org/10.5281/zenodo.22655833
D6	Summary report on the developed software ecosystem for light dosimetry data analysis. In particular, the report will summarise the development of: • Package for analysis, validation and processing of light dosimetry data • Web platform and package for converting data packages • Package for visualisation of light dosimetry data • Instruction manual for the use of the software	PU - Public, fully open	https://doi.org/10.5281/zenodo.21621188
D7	Evaluation report on the performance of spatially resolved devices measuring photobiological quantities. The report will include performance comparison between spatially resolved and spatially averaging devices per use case, and include conclusions on their benefits and drawbacks.	PU - Public, fully open	https://doi.org/10.5281/zenodo.21625838
D8	Letter from CIE Division 2 and 6 confirming that the project results related to the optical characterisation of wearable light loggers have been submitted for consideration in their potential incorporation in new standards	PU - Public, fully open	https://doi.org/10.5281/zenodo.22940686

n/a	Data management plan	PU - Public, fully open	https://doi.org/10.5281/zenodo.22692561

Project start date and duration:		1 June 2023, 36 months
Coordinator: Fabien Eloi, LNE E-mail: fabien.eloi@lne.fr Project website address: https://melidosproject.github.io/.github/		
Chief Stakeholder Organisation: International Commission on Illumination (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		