Towards a framework for light-dosimetry studies: Methodological considerations

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Abstract

For field research of non-visual effects of light, accurate measurement of personal light exposure is required. A consensus framework for light-dosimetry could improve non-visual field research and ensure comparability between studies. Here we present a review of methodologies used in non-visual light-dosimetry studies published to date, focussing on considerations regarding the measurement and preparation of personal light exposure data. Overall, a large variability in the studies' methodologies is observed, highlighting the need for a consensus framework. We propose methodological considerations that should be included in such a framework and that can guide future studies. Furthermore, we highlight important points that should be addressed in future research to ensure compatibility between different dosimetry studies. Taken together, this review effort underlines the importance of a systematic approach to light-dosimetry in order to harness all the power of integrative lighting research in real-life.

Keywords: Non-visual, Dosimetry, Lighting, Circadian, Field studies, Daylight

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1. Introduction

Decades of research have shown that light has behavioural and physiological effects unrelated to human vision, mediated by a dedicated neural pathway. Through this pathway, light sets our biological clock,[1] directly affects various aspects of physiology and behaviour,[2] and may thereby be related to health and wellbeing.[3] Much of what is known about these non-visual effects of light has been established by extensive laboratory research, indicating that responses are modulated by different light exposure characteristics.[4] However, real-life light exposure resembles nothing like laboratory stimuli, but consists of complex patterns of light of different quantity and quality, as a result of moving

through our indoor and outdoor environments. Therefore, more field research is needed to complement and evaluate findings from controlled laboratory studies, and answer pressing questions pertaining to implications in applied contexts, such as architecture and lighting design, therapeutical applications, shift-work, transcontinental travel, and personal lifestyle.[5]

Due to the complexity of personal light exposure patterns and the uncontrolled nature of field research, it is crucial that results from different studies are comparable and repeatable, as well as transferable to applied contexts. This can be achieved by agreeing on standardised operating procedures for setting up and reporting lighting research studies.[5] A crucial aspect in non-visual lighting research is the accurate description of the lighting conditions under investigation. For experimental studies, guidelines for quantifying and reporting lighting conditions have recently been published.[6–8] However, these guidelines have only limited applicability for field research, where light exposure cannot be controlled. Thus, to date it is still unclear how to adequately measure, quantify, and analyse personal light exposure data with respect to non-visual responses.

Given the complexity of light exposure and its relationship with non-visual responses in real-life, accurate measurement of personal light exposure (i.e., dosimetry) is crucial. The dosimetry process – also called the dosimetry chain – consists of a series of steps (links), each of which has the potential to introduce additional uncertainty in the final research outcome.[9] Broadly, these links can be categorised as (1) selecting optical quantities, (2) calibrating dosimeters, (3) selecting a measurement setup, (4) processing the measured data, (5) calculating light exposure metrics, and (6) linking metrics to measured responses.[9] Importantly, different execution of each link may lead to substantial differences in the results, complicating their interpretation and comparison across studies. Therefore, agreement on standardised procedures for each link is urgently needed.[9]

In the present article, we set out to laying the groundwork for a consensus framework for non-visual light-dosimetry studies. To achieve this, we assembled a comprehensive set of dosimetry field studies published to date, which is taken as a basis for discussing methodological considerations for each link in the dosimetry chain. Herein, we review methodologies employed in previous dosimetry studies for measurement and preparation of personal light exposure data. Furthermore, we aim to identify crucial gaps in knowledge that need to be specifically addressed and clarified in future research.

As a brief note on nomenclature, throughout this article, the term *light exposure* is used to refer to the time series of light a person is exposed to and not to the quantity *luminous exposure* H_V. Furthermore, the term *light level* is used as a generic term where multiple light quantities are applicable within a given context (e.g., illuminance, alpha-opic irradiance etc).

2. Review method

2.1 Search strategy

To collect a comprehensive set of light-dosimetry field studies, a forward and backward citation search method was used, allowing for an efficient assembly of relevant studies within the same domain. Two of the first light-dosimetry studies in the context of chronobiology were chosen as a starting point,[10,11] from which eligible dosimetry studies published to date were identified by means of forward and backward citation search using the Web of Science citation database (forward and backward search) and the individual papers' reference list (forward search), within the period of January–March 2021.

2.2 Selection criteria

The main objective of this review was to identify light-dosimetry studies that covered the entire dosimetry chain from measurement to quantification and subsequent analysis of the collected light exposure data, the ultimate intent being to highlight methodological considerations in the dosimetry procedure and to identify metrics for the quantification of personal light exposure patterns. Therefore, studies were only eligible if personal light exposure data was measured with wearable light meters over a period of at least 24 hours and if the measured light data was included as a dependent or independent variable in the analysis. This criterion excluded studies that measured 24h-light exposure with static devices only (i.e., the device was not worn by the subject) or that measured light exposure but did not report any analyses of these measurements. Consequently, many intervention studies where personal light exposure was monitored but not analysed as a major dependent or independent variable were excluded, except for three studies. Specifically, the study by Peeters *et al.*[12] was included because personal light exposure was a primary dependent variable in the analysis, and Phillips *et al.*[13] and Zeitzer *et al.*[14] were included because multiple light exposure metrics were analysed.

In addition, to narrow the scope of this review, we primarily focused on dosimetry studies in the context of the non-visual effects of light; specifically, pertaining to sleep-wake regulation, circadian entrainment, and direct physiological and behavioural responses (e.g., alertness, cognitive performance, mood etc.). As a result, studies that measured personal light exposure in a different context (e.g., myopia, UV-light) were excluded, except for three myopia-related studies where the methodology added novel content to the review. Specifically, the studies by Alvarez and Wildsoet[15] and Ulaganathan *et al.*[16] were included because effects of sampling frequency on the accuracy of calculated light exposure metrics were investigated. Moreover, the study by Read *et al.*[17] was included because metrics are described that have not been used in any of the other studies already included in the review.

2.3 Final Set of Studies

In total, 104 studies were deemed eligible and formed the set of dosimetry field studies reviewed here. An overview of the selected studies[10–113] and study related characteristics is presented in the appendix (Table A1.1).

3. Methodological considerations

3.1 Dosimetry setup and measurement

3.1.1 Dosimeter selection and optical quantities

Personal light exposure is usually measured with lightweight wearable devices (dosimeters; see Figure 1). A wide range of different technologies exists on the market, reflected in the variety of dosimeters employed by the reviewed dosimetry studies (see Table 1). The dosimeters can broadly be categorised into dedicated light meters or wrist-worn actigraphy devices with light sensors (note that most wrist-worn dosimeters can also be adapted to be worn elsewhere). Furthermore, devices differ in their spectral sensitivity and resolution. Most devices listed here measure photopic illuminance (e.g., *Actiwatch-L*), or spectral irradiance in the visible range across three channels (red, green, blue; e.g., *Actiwatch Spectrum*). Three devices include a sensor calibrated to approximate the circadian spectral sensitivity (i.e., LuxBlick, Daysimeter, Dimesimeter), while only two dosimeters were used that have a higher spectral resolution.

The optical quantities a dosimeter can measure is an important consideration for non-visual dosimetry, since the spectral composition of personal light patterns (i.e., the "relative spectral diet", see Webler *et al.*[115]) can drastically vary over time. While historically, dosimeters have been developed to measure light for the visual system (i.e., photometric), we now know that the description of light in photometric terms is usually not appropriate when studying non-visual effects of light.[116] Consequently, new standards such as CIE S 026:2018[117] were developed, defining spectral sensitivity functions, quantities, and metrics to describe light for non-visual responses (i.e., alpha-opic quantities).

Currently the main limitation for the measurement of alpha-opic quantities is the limited availability of dosimetry devices that spectrally match the alpha-opic sensitivities. With the exception of devices used in two studies,[19,26] none of the dosimeters listed here match all alpha-opic sensitivities with sufficient accuracy.[118] Only one of the commercially available devices (i.e., the *Actiwatch Spectrum*) approximates the melanopic sensitivity function by a linear combination of photosensor outputs.[118] Note that the *ActTrust* dosimeter can be modified to provide a sufficient spectral match to the melanopic sensitivity curve as described previously[119]; however, no study in this review used this modified device. Given that the melanopic sensitivity curve matches the sensitivity of non-visual responses for a wide range of conditions, as suggested in a recent comprehensive review of several experimental studies,[120] dosimetry studies could use devices that match this curve (see [66,69,81]) until

sufficiently spectrally resolved devices become available. Such devices could contain broadband photosensors matching the alpha-opic sensitivities directly (i.e., analogous to the sensor in the *Daysimeter*); however, these sensors are then constrained by assumptions on the underlying neurophysiology. Therefore, devices from which (parts of) the visible spectrum can be sufficiently recovered in order to calculate alpha-opic quantities offer a significant advantage over the former type of devices, as further elaborated on in the Discussion section.

3.1.2 Dosimeter assessment and calibration

Light-dosimeters have been found to vary substantially in optical performance between and within models as assessed in a range of studies.[118,121–123] Many of the devices assessed in these specific performance assessment studies were used by the reviewed dosimetry studies. However, only some of the reviewed studies (N=26) report that dosimeters were validated and calibrated against an industry-standard light sensor (Figure 2A). Among the studies that provided a description of the validation and calibration procedure (N=19), a variety of methods were used: notably, validation was performed for different reference lighting conditions, including artificial light sources (N=13), simulated daylight (N=2), and/or under naturalistic indoor or outdoor conditions (N=6).

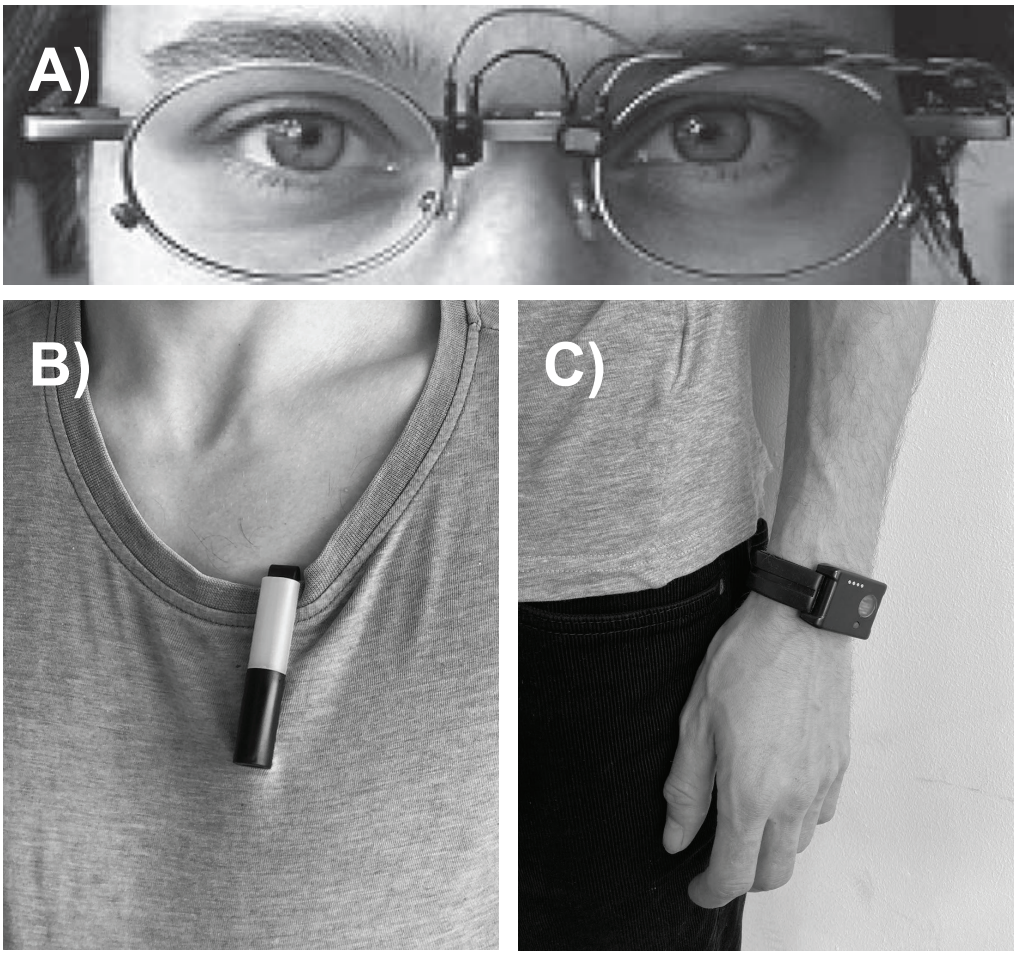

Figure 1. Example of different dosimeter types and positions: **A)** *LuxBlick* light-dosimeter for measurement at eyelevel (image retrieved from Hubalek *et al.*[56]), **B)** *Spectrace*[141] light-dosimeter worn at the chest, **C)** *ActTrust* wrist-worn actigraphy and light-dosimetry device.

The diversity of calibration methods used in dosimetry studies highlights the need for standardised assessment and calibration procedures. Typically, optical performance of photometers is assessed in terms of spectral sensitivity, directional response, and response linearity as defined in the standard ISO/CIE 19476:2014.[124] However, current standards are not readily applicable for the characterisation of light-dosimeters for non-visual effects research, therefore novel methods are needed.[118] Published optical performance metrics can help guiding the selection of an appropriate dosimeter for a given study. For non-visual effects research, devices that have good spectral sensitivity for matching the five α-opic sensitivity functions should be preferred.[117] However, trade-offs between spectral and directional mismatch should be considered, since the arrangement of multiple photosensors may affect directional responses.[118] The impact of directional mismatch may also depend on where the device is worn and how the data is aggregated. That is, high movement at the wrist or aggregation over longer time periods may cancel out directional mismatches.[125] Moreover, the linear range and dynamic resolution that is required should be considered depending on the lighting conditions expected in the study.

The standard ISO/CIE 19476:2014[124] also describes calibration procedures for photometry devices; however, this standard may not be applicable to dosimeters that measure non-photometric quantities (e.g., spectral irradiance, alpha-opic irradiance). As a result, several methods have been described by individual studies.[122,126–128] An important aspect to consider during calibration is the selection of a calibration light source that matches the lighting conditions typically encountered during the study. For studies with various lighting conditions, it has been recommended to calibrate devices to an overcast sky at noon,[122] or by averaging across several light sources.[129] Note that ambient conditions (i.e., temperature and humidity) can also substantially impact sensor accuracy and, ideally, should be calibrated for accordingly. However, this calibration is difficult for the many available light-dosimeters that do not include sensors to measure ambient conditions.

3.1.3 Dosimeter position

For research on the non-visual effects of light, the amount of light reaching the eye (corneal light exposure) is of primary interest; therefore, the position of the dosimeter on the body is an important consideration. Among the reviewed studies, only very few measured light exposure at eye-level (N=9), whereas most measured at the wrist (N=67) and some at the chest (N=22; Figure 2B). Measurements at eye-level require a specific setup (e.g., *LuxBlick*; see Figure 1) and might be perceived as more obtrusive than at the wrist or chest, [130] which may explain the small number of studies measuring at this position. While both wrist and chest measurements may be less obtrusive, the large number of studies measuring at the wrist can be partly explained by the frequent use of actigraphy devices, allowing concomitant measurement of light exposure and sleep-wake activity within a single device. Only few studies measured actigraphy at the wrist and light at another position with separate devices (N=12), or with a single device that is transferred to the wrist for actigraphy during sleep (N=3).

Table 1. Overview of dosimeter models used in previous studies sorted by frequency of use.

Device Name	Manufacturer	Primary purpose	Output	N
Actiwatch-L	MiniMitter (now Philips Respironics)	Actigraphy	E_v	25
Actillume	Ambulatory Monitoring Inc.	Actigraphy	E_v	14
Actiwatch 2	Philips Respironics	Actigraphy	E_v	12
Actiwatch Spectrum	Philips Respironics	Actigraphy	W, R, G, B	10
Daysimeter	Lighting Research Center	Light	E_v, CS	6
HOBO Pendant	Onset Computer Co.	Light	E_v	6
Actiwatch-L	CamNtech Ltd.	Actigraphy	E_v	4
Dimesimeter	Lighting Research Center	Light	E_v, CS	3
MotionWatch 8	CamNtech Ltd.	Actigraphy	E_v	3
StowAway	Onset Computer Co.	Light	E_v	3
Custom	various	various	E_v	3
Actiwatch Plus	Philips Respironics	Actigraphy	W, R, G, B	2
GeneActiv	Activinsights Ltd.	Actigraphy	E_v	2
Lightlog	LightlogProject	Light	W, R, G, B	2
Actiwatch RGB	CamNtech Ltd.	Actigraphy	W, R, G, B	1
ActTrust	Condor Instruments	Actigraphy	W, R, G, B	1
CSA AM	Computer Science Applications Inc.	Actigraphy	E_v	1
Daqtometer 2.4	Daqtix GmbH	Actigraphy	E_v	1
LightWatcher	Object-Tracker	Light	W, R, G, B, UV, IR	1
LuxBlick	Hubalek *et al.*[56]	Light	E_v, E_c	1
MotionLogger-L	CamNtech Ltd.	Actigraphy	E_v	1
RaySeG	Eto *et al.*[38]	Light	R, G, B, UV	1
Sleepwatch-L	Ambulatory Monitoring Inc.	Actigraphy	E_v	1
Custom	Adamsson *et al.*[19]	Light	Range 400-750 nm (50 nm res.)	1
Custom	Cain *et al.*[26]	Light	Range 340-780 nm (15 nm res.)	1

Note: E_v = Illuminance, W = white light, R = long-wavelength irradiance, G = medium-wavelength irradiance, B = short-wavelength irradiance, UV = ultra-violet light, IR = infrared light, CS = Circadian Stimulus, E_c = irradiance weighted by $c(\lambda)$[114]. This table does not list all available devices, but only devices that were used in the reviewed studies.

As most studies did not measure light exposure at eye-level, it is important to study to what extent corneal light exposure can be estimated from measurements at other positions. Yet surprisingly few studies have addressed this question. An early study that is frequently cited reported high correlation between measurements at the wrist and the forehead;[10] however, the validity of these findings is limited due to dosimeter saturation at higher illuminance levels. Furthermore, correlation does not show the amount and direction of deviations at different light levels. Another study in postsurgical in-hospital patients reported little average deviation (<10 lx) between wrist and eye-level measurements up to 5000 lx;[131]however, the findings may not be generalisable to normal living conditions. To our knowledge only one study examined different measurement positions under normal living conditions for an extended period, reporting little deviation between illuminance at eye-level and the chest, but large deviation for the wrist, which generally underestimated eye-level exposure, especially at higher illuminance levels.[125]

While this preliminary evidence suggests that measurements at the chest may be more accurate than at the wrist for estimating corneal light exposure, systematic variations in measurements at different positions should be considered. Aarts *et al.*[123] found that both wrist and chest measurements

deviated substantially more from eye-level measurements under indoor conditions compared to outdoor conditions, which was especially pronounced for wrist measurements. Moreover, under indoor conditions wrist measurements tended to overestimate and under outdoor conditions underestimate eye-level exposure, corroborating earlier studies. Additionally, under indoor conditions, systematic variations have been observed for different activities, body postures and gaze directions.[132] Interestingly, this study also found that the exposure threshold associated with phase shifts of dim light melatonin onset (DLMO) estimated from eye-level measurements was not associated with phase shifts when using the same threshold for wrist measurements, likely due to overestimation of eye-level exposure.

3.1.4 Recording interval

In light-dosimetry the recording interval or *epoch length* defines the rate at which individual light exposure measurements are recorded and therefore determines the temporal resolution and accuracy at which changes in light exposure can be captured. Among the studies under review, epoch lengths ranged from 100ms to 5min, with 1min and 30s being the most used (N=51 and N=16, respectively; Figure 2C). Note that these epochs indicate the rate at which samples are recorded but do not necessarily reflect the sampling rate of the photosensors, as some dosimeters record an aggregated value of several samples across the given interval.

Epoch lengths are usually selected to optimise battery and memory usage, since dosimeters are often employed continuously for several days in a row. However, while longer epochs may help to conserve battery power and reduce memory load, the accuracy with which light exposure is measured may be affected, resulting in a trade-off between battery/memory usage and accuracy. For example, it has been found that epochs of 3min or longer lead to a loss of accuracy relative to shorter epochs when calculating cumulative light exposure and time spent under bright light conditions.[15,16] On the other hand, while longer epochs may reduce accuracy, it is not yet known how much interpretability is gained by increasing recording rate.

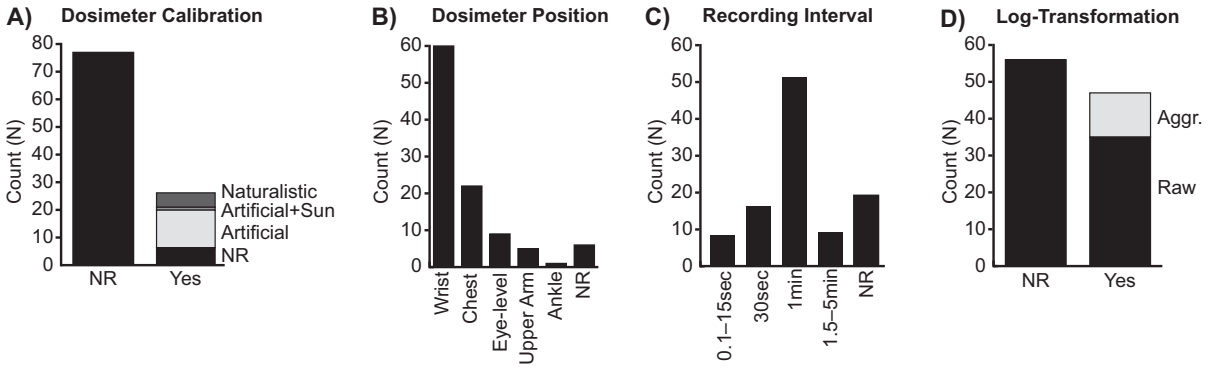

Figure 2. Frequency of methods used across the reviewed studies: **A)** dosimeter calibration and, if applicable, calibration light sources, **B)** dosimeter positions, **C)** recording intervals, and **D)** log-transformation sequence (*Aggr*. = transformation of aggregated data, *Raw* = transformation of raw data). NR = not reported.

3.2 Data preparation

3.2.1 Data cleaning

Due to the uncontrolled nature of light-dosimetry, measured data may contain invalid or artifact data. Two major sources of invalid data are periods where the dosimeter was not worn or when the light sensors were obstructed. Invalid periods were identified by some studies (N=18) based on concomitant inactivity longer than a given timeframe, which ranged from 5–120min across studies. Some studies additionally examined the light data for smooth periods with little fluctuation, indicating invalid periods. [31,69,81] Furthermore, several methods for identifying measurement artifacts due to sensor obstruction have been reported. Some studies (N=13) identified artifacts as light measurements below a threshold value during day- or wake-time, ranging from 0–10 lx across studies. Other methods involved the identification of temporary drops in the data,[26] unusually high rate of change,[74] and outlier detection methods.[105] Moreover, some studies removed remaining noise in the data with smoothing methods, by using simple moving average (SMA) filters with different window sizes between 5–20min,[32,79,85,104] or local regression smoothing (LOESS).[108] The latter procedure preserves peaks in the signal better than a SMA filter, but it can be computationally expensive for large datasets. Note that smoothing methods can also be used as an analytical procedure; for example, to quantify light dose in time by mimicking non-visual response characteristics.[81] Beside smoothing, some studies (N=15) averaged the data into bins (e.g., hourly averages), which can also be considered a means to remove noise in the data. However, as with smoothing methods, it is important to consider logarithmic transformation when aggregating data, as discussed in the next section.

Although cleaning measured personal light exposure data is an important step in the dosimetry process, nearly no studies have systematically investigated what cleaning methods and parameters are most appropriate for these kinds of data. To our knowledge, only one study has examined identification thresholds for sensor obstruction, showing that dosimetry measurements in a very dim laboratory environment without coverage by clothing did not fall below 1lx.[88]

3.2.2 Logarithmic Transformation

Personal light exposure data can cover a large range of light levels over several orders of magnitude and usually follow a log-normal distribution.[133] Therefore, analyses may require logarithmic transformation of the data to ensure a normal distribution and enable interpretability. An important consideration when applying log-transformation is the sequence in which the data is transformed, aggregated, and analysed, particularly regarding the question whether the transformation should be applied *before* or *after* quantifying the "raw" light data. Amongst the reviewed studies, less than half applied a log-transformation, either before (N=35) or after (N=12) quantification (Figure 2D). A major rationale for transforming the data was to ensure normality for statistical analyses (N=10). Interestingly, four studies provide an explicit rationale for transforming raw data,[65,92,108,109] referring to

log-linearity observed in non-visual dose-response curves.[134,135] Contrastingly, Scheuermaier *et al.*[88] argue that log-transformation should be applied after aggregating the data, in order to account for brief episodes of very bright light.

Indeed, the sequence of log-transformation may substantially affect the results. Take for example the hypothetical light exposure pattern of an office worker between 12:00–13:00h, who during work is exposed to 200 lx and who goes outside for a lunch break at 12:30h, being exposed to 10000 lx. The calculated hourly means for this individual would be around $10^{3.71}$ (~5100 lx) with log-transformation after aggregation, and $10^{3.15}$ (~1400 lx) with log-transformation before aggregation. Realistically this difference could be even greater depending on the fluctuation of light levels. This potentially huge impact on aggregated light exposure makes it impossible to compare data such as mean hourly light exposure between studies that aggregated and transformed the data in a different sequence. Moreover, analyses of non-visual responses may be affected, such as when using linear models to examine acute effects of hourly light exposure. Note that although it can be argued that mean light exposure may not be the right metric to analyse non-visual effects, it is still the most widely used metric to describe and compare personal light exposure patterns across all studies reviewed here.

Logarithmic stimulus-response relationships are well established in psychophysics (i.e., *Fechner's law*), and non-visual responses to light are no exception: logarithmic relationships to light intensity have been described for circadian phase resetting,[136] melatonin suppression,[134] and acute alertness.[135] Some findings from cell recordings suggest that logarithmic encoding of light intensity may happen at the level of retinal ganglion cells, whose neuronal firing response is directly proportional to the detected amount of photons on a logarithmic scale.[137–139] However, no study has yet specifically addressed what these findings imply for the measurement of time-series light exposure data.

4. Discussion and recommendations

In this review we presented an overview of methods employed by previous dosimetry studies to measure and prepare personal light exposure data. Overall, a large variability in methodologies was observed across all studies. Personal light exposure was measured with a variety of dosimeters, at different positions on the body, and with different recording intervals. Very few studies measured spectrally resolved light exposure. Dosimetry devices were often not reported to be calibrated, and studies that calibrated the devices used a variety of different methods. Regarding data preparation, the few studies that report data-driven cleaning procedures used several different methods and parameters to identify invalid light exposure data. Discrepancy was also observed in the application and sequence of log-transformation of the light data. In the following, we briefly discuss methodological implications based on these findings and provide recommendations for future dosimetry studies, as well as important points that need to be addressed in future research.

4.1 A note on accuracy in dosimetry for non-visual effects of light

As emphasized throughout this review, research of non-visual effects demands an accurate description of lighting conditions to improve the validity of research findings and ensure comparability and transferability of results across studies.[7] This holds especially for dosimetry, to avoid additional uncertainty in the presence of the plethora of confounders in field research. However, since an increase in accuracy often comes at the expense of factors such as practicality and cost, one of the central questions in dosimetry is how much accuracy is required at each dosimetry step, for analysing the relationship between measured non-visual responses and light exposure.

Given that dosimetry inherently refers to the study of the absorption of a physical quantity by the human body, it makes sense that dosimetry methods and metrics are biologically relevant. In theory, many of the methods discussed in this review could be based on neurophysiological mechanisms, for example, using smoothing methods that reflect temporal integration of the light signal. However, one of the central challenges in dosimetry is that our understanding of the mechanisms underlying signal encoding, adaptation, and photic integration in the non-visual system is still incomplete. These uncertainties make it difficult to define accuracy limits for spectral and temporal resolution, and dynamic range, which is further complicated by large inter-individual differences in light sensitivity.[140] In light of these uncertainties, instead of basing accuracy limits on assumptions of the underlying biology, it might be more appropriate to consider how the physical signal itself can be measured more accurately within the given technological and practical constraints, for instance, by using information theoretic approaches (see Section 4.3).

4.2 A proposal for guidelines and recommendations

Based on the findings of this review we propose guidelines and recommendations for future dosimetry studies, summarised in Table 2. It is important to note that these recommendations are based on current knowledge, while several points demand further investigation (see Section 4.3). Therefore, it is crucial that methods and parameters used at each step in the dosimetry process are reported in necessary detail, either in the article itself or provided in the supplementary material. Insufficient reporting hinders transparency, reproducibility, and comparability, which is essential for research of non-visual effects in the field to be successful.

A crucial aspect in dosimetry is the selection of an appropriate dosimeter model, which depends on the context and aims of a given study. For research on the non-visual effects of light, devices that spectrally match the alpha-opic sensitivity curves should be preferred; however, given current limited availability of such devices, at least dosimeters that match the melanopic sensitivity curve should be used. In any case, we strongly recommend to always validate and calibrate dosimeters, and report a (reference to the) description of the calibration setup and procedure, including at least the calibration light sources used and which type(s) of calibration were performed (e.g., spectral, intensity, temperature calibration).

Table 2. Proposed guidelines and recommendations for dosimetry studies

Issue	Recommendation
Dosimeter Selection	• Select dosimeters with a spectral resolution appropriate to the aim of the study: for research on non visual responses, ideally, select devices that spectrally match the alpha-opic sensitivities. • Consider optical performance characteristics in relation to study context and measurement setup.
Calibration	• Calibrate devices; Select reference light sources based on study context. • Report description of validation and calibration procedure, including the reference light sources used.
Dosimeter Position	• Position dosimeter at eye-level for precise measurements, otherwise at chest. Use dosimeter in tandem with wrist-actigraphy if needed. • Consider context dependent direction and amount of deviation from corneal exposure. • Consider obtrusiveness and practical issues; Carefully instruct participants to avoid sensor obstruction.
Recording Interval	• Select shortest epoch possible to achieve desired battery life. • Avoid epochs longer than 2min.
Data Cleaning	• Use data-driven methods to verify or replace subjective reports. • Use multiple variables to identify invalid periods (e.g., light exposure and activity). • Explain how and why given methods and parameters are selected.
Log-Transformation	• Consider the impact of log-transformation sequence; Compare analyses for different sequences. • Report geometric means alongside arithmetic means.

Another important consideration are contextual factors, such as lighting conditions, environments, activities, and body positions expected during the study. These factors may determine the amount and direction of deviation from corneal exposure for different measurement positions, which can affect the analysis of non-visual responses. For example, using sensitivity thresholds based on corneal exposure for the analysis of light exposure measured at the wrist under predominantly indoor conditions may prevent detecting an effect, due to overestimation of corneal exposure. Similarly, contextual factors should be considered for selecting dosimeter models, calibration light sources, and data cleaning methods.

Furthermore, dosimetry methods should be selected to achieve the highest accuracy within the given study constraints, avoiding assumptions on the underlying biology. The latter is particularly important for data preparation, as it is still unclear how the non-visual system encodes and integrates light information over time. Therefore, we recommend evaluating a range of different methods and parameters during analyses and include a detailed description of the selected cleaning methods and transformation sequence. Moreover, alongside the arithmetic mean, the geometric mean and/or other measures of central tendency should be reported.

4.3 Future work

While the proposed recommendations given above are based on current knowledge and may form the basis of a framework for non-visual light dosimetry, we have identified several important points that need to be addressed in further research for such a framework to be able to become fully operational (see Table 3). Importantly, more research investigating systematic interactions between factors related to the study context (e.g., lighting conditions, activities etc.) and dosimetry methods are urgently needed, for example, to evaluate different dosimeter positions or improve data cleaning methods. On a long-term basis, more research studying underlying neurophysiological mechanisms such as photic

integration and sensitivity adaptation is required to inform dosimetry methods. Such research would be especially insightful regarding the sequence of logarithmic transformation, given the widespread use of this method in dosimetry data analysis.

To facilitate the development of a future consensus framework and standards for light-dosimetry, it is of interest to examine in how far current standards in light metrology can be recycled and adapted. For example, the CIE already proposes standards for the calibration and performance characterisation of photometers (ISO/CIE 19476:2014[124]). However, these standards are limited to photometric measurements, and may not be appropriate for the measurement of alpha-opic quantities as recommended in the new standard CIE S 026:2018[117]. Some suggestions for how these standards can be adapted have already been put forward by Price *et al.*[118]. Similarly, an effort for developing consensus reporting standards for light-intervention studies (ENLIGHT[141]) is currently under way, which could in future be expanded to light-dosimetry in general. Such reporting standards may also contain guidelines for reporting the intended use of light-dosimetry in intervention-studies, since intervention studies often make little use of collected dosimetry data.

In parallel, information theoretic approaches focussing on increasing measurement accuracy within the given technological and practical constraints should be explored. Specifically, novel data-driven methods may be used to increase spectral and temporal resolution of dosimeters, as described in a complementary paper[142] and briefly introduced in the following. Spectral and temporal resolution historically have been constrained by technological limits to size, weight, power, and cost of dosimeters. However, recent advances in sensor technology and signal processing methods, such as *compressed sensing,*[143] challenge conventional limitations. Such methods demonstrate that for compressible (i.e., non-random) signals, the amount of information encoded can be much smaller than prescribed under classic sampling theorems. Compressed sensing effectively finds the simplest representation of a signal by exploiting regularities in the structure and properties of encoded signals. In practice, sensors based this method can reduce the amount of encoded information at the source by a factor of 10,[144] enabling high spectral resolution at a small size and cost. Recent work on a compressed sensing dosimeter named *Spectrace*[145], developed by the authors, has already demonstrated the ability to recover 5 nm resolution data over the visible range from 14 narrowband photodiodes,[142] all in an autonomous wearable form no larger than a USB stick. As with compressed spectral sensing, sparse representation and forecasting can also be used to construct adaptive sampling rates that respond to changes in the environment (e.g., sample more when the scene changes and less when it is stable). Such approaches offer low-power and compact hardware forms without information loss. Taken together, information theoretic approaches offer novel ways of increasing accuracy in dosimetry within the given constraints, while avoiding the uncertainty introduced by making assumptions on human biology.

Table 3. Important points to be addressed in further research

Outlook	Point to address
Short-term	• Evaluation of optimal reference light source(s) for dosimeter calibration. • Development of standardised calibration protocols. • Investigation of the effects of different lighting conditions and activities on measurements at different positions. • Evaluation, validation, and development of new and existing data cleaning methods. • Investigation of the effects of transformation sequence on dosimetry outcomes. • Exploration of novel information theoretic approaches to increase measurement accuracy within constraints.
Long-term	• Investigate neurophysiological mechanisms to inform dosimetry methods and metrics.

5. Conclusion

With this article we discuss the status quo in dosimetry methodology to form a basis for further work towards a consensus framework for light-dosimetry studies. This review is the first to highlight the prevalent variability in methodologies employed by light-dosimetry studies during the past three decades, underscoring the need for standardised operating procedures to improve the comparability and repeatability of dosimetry studies. Moreover, by collecting this diverse set of methodologies, we were able to reveal important gaps in knowledge that need to be addressed in further research. At the same time, we show what methods are available for measuring and preparing personal light exposure, and what to consider and avoid when conducting light-dosimetry studies. With this work we would like to bring the topic of light-dosimetry to greater attention, with the hope to provide researchers with the required knowledge to perform high quality studies and inspire more research in this direction. Furthermore, we want to emphasise the importance of carefully considering each step in the dosimetry process as each methodological decision may substantially affect the final study results. In the forthcoming second part of this review, methods for quantifying and analysing personal light exposure with respect to the non-visual system will be discussed.

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Table A1.1. Overview of the dosimetry studies included in the review

Authors	N	Sample	Dosimeter	Position	Actigraphy setup	Recording interval	Calibration	Quantities	Log-transformation
aan het Rot *et al.*[18]	48	SAD patients	Actiwatch-L	Wrist	Single	2min	-	E_v	-
Adamsson *et al.*[19]	15	Office-workers	Actiwatch-L, Custom	Wrist, Chest	Tandem	1min	Art. + Sun	E_v, R, G, B, M	-
Akacem *et al.*[20]	21	Children	Dimesimeter	Chest	Tandem	1min	-	E_v	-
Alvarez *et al.*[15]	27	Students	HOBO Pendant	Upper arm	None	10s	-	E_v	-
Asai *et al.*[21]	1005	Eldery	Actiwatch 2	Wrist	Single	1min	-	E_v	-
Auger *et al.*[22]	38	DSPD patients	Actiwatch-L	Wrist	Single	1min	-	E_v	Aggr.
Böhmer *et al.*[23]	48	Elderly	HOBO Pendant	Chest	Tandem	1min	Nat.	E_v	Raw
Borugian *et al.*[24]	17	Shift-workers	StowAway	Chest	None	30s	-	E_v	-
Boubreki *et al.*[25]	21	Office-workers	Actiwatch-L	Wrist	Single	30s	-	E_v	Raw
Cain *et al.*[26]	59	General pop.	Custom	Chest	Tandem	2min	Art. + Sun	E_v, mEDI	Raw
Campbell *et al.*[27]	23	Eldery	Custom	Wrist	Single	1min	No descr.	E_v	-
Cole *et al.*[28]	54	General pop.	Actillume	Wrist, Chest	Tandem	1min	Art.	E_v	Raw
Crowley *et al.*[29]	14	Office-workers	Actiwatch Spectrum	Chest	Tandem	30s	-	E_v	Raw
Darling *et al.*[30]	32	Postmenop. women	Actiwatch-L (CamNtech)	Wrist, Chest	Tandem	1min	-	E_v	-
Daugaard *et al.*[31]	341	Shift-workers	Actiwatch Spectrum	Upper arm	Transfer	1min	Nat.	E_v	-
Daugaard *et al.*[32]	485	Indoor-, Outdoor-, Shift-workers	Actiwatch Spectrum	Upper arm	Transfer	1min	Nat.	E_v	Aggr.
Dumont *et al.*[33]	30	Shift-workers	Actillume	Wrist	Single	1min	Art.	E_v	Raw
Dumont *et al.*[34]	13	Shift-workers	Actiwatch-L	Chest	None	1min	Art.	E_v	Raw
Emens *et al.*[35]	66	General pop.	Actiwatch-L	Wrist	Single	30s	-	E_v	Raw
Esaki *et al.*[36]	181	BD patients	Actiwatch Plus	Wrist	Single	1min	-	E_v	-
Espiritu *et al.*[37]	150	General pop.	Actillume	Wrist	Single	-	-	E_v	Raw
Eto *et al.*[38]	39	Office-workers	RaySeG	Eye	None	1ms	-	R, G, B	-
Feigl *et al.*[39]	21	General pop.	Geneactiv	-	Single	-	-	E_v	Aggr.
Figueiro & Rea[40]	12	Adolescents	Daysimeter	Eye	None	30s	No descr.	E_v, CLA	-
Figueiro *et al.*[41]	37	Eldery	Dimesimeter	Wrist	Single	-	-	CS	-
Figueiro *et al.*[42]	109	Office-workers	Daysimeter	Chest	Transfer	90s	No descr.	CS	-
Flanagan *et al.*[43]	51	General pop.	Actiwatch 2	Wrist	Single	30s	-	E_v	-
Gibbs *et al.*[44]	23	Shift-workers	Actiwatch-L	-	Single	1min	-	E_v	-
Goulet *et al.*[45]	19	General pop.	Actiwatch-L	Wrist	Single	1min	Art.	E_v	Raw
Grandner *et al.*[46]	459	Postmenop. women	Actillume	Wrist	Single	1min	-	E_v	Raw
Grundy *et al.*[47]	61	Shift-workers	StowAway	Chest	None	5min	-	E_v	Aggr.
Grundy *et al.*[48]	123	Shift-workers	StowAway	Chest	None	1min	-	E_v	Aggr.
Guillemette *et al.*[49]	19	General pop.	Actillume	Wrist, Chest	Tandem	1min	-	E_v	-
Gumenyuk *et al.*[50]	10	Shift-workers	Actiwatch-L	Wrist	Single	-	-	E_v	-

(*Continued*)

Table A1.1. (Continued)

Authors	N	Sample	Dosimeter	Position	Actigraphy setup	Recording interval	Calibration	Quantities	Log-transformation
Hall *et al.*[51]	102	Shift-workers	Daysimeter	Chest	None	1min	-	E_v	-
Harb *et al.*[52]	20	Hospital staff	Actiwatch 2	Wrist	Single	1min	-	E_v	-
Hebert *et al.*[53]	16	General pop.	Actillume	Wrist	Single	1min	-	E_v	-
Heil & Mathis[54]	11	Hospital staff	CSA	Wrist	Single	1min	-	E_v	-
Higgins *et al.*[55]	2	Eldery	Daysimeter, Sleepwatch-L	Eye, Wrist	Tandem	-	No descr.	E_v, CS	-
Hubalek *et al.*[56]	23	Office-workers	LuxBlick	Eye	None	100ms	-	E_v, E_C	-
Jean-Louis *et al.*[57]	224	General pop.	Actillume	Wrist	Single	1min	-	E_v	Raw
Jean-Louis *et al.*[58]	30	General pop.	Actiwatch-L	Wrist	Single	1min	-	E_v	Raw
Joo *et al.*[59]	68	DSPD patients	Actiwatch-L	Wrist	Single	-	-	E_v	Aggr.
Kawinska *et al.*[60]	37	General pop.	Actiwatch-L	Wrist	Single	1min	Art.	E_v	Raw
Keller *et al.*[61]	38	Adolescents	Daqtometer 2.4	Wrist	Single	10s	-	E_v	-
Kim *et al.*[62]	182	Insomnia patients	Actiwatch 2	-	Single	1min	-	E_v	Raw
Koller *et al.*[63]	12	Shift-workers	Custom	Eye	None	15s	-	E_v	-
Koller *et al.*[64]	12	Shift-workers	Custom	Eye	None	30s	-	E_v	-
Kripke *et al.*[65]	459	Postmenop. women	Actillume	Wrist	Single	-	-	E_v	Raw
Lee *et al.*[66]	33	Old Order Amish	Actiwatch Spectrum	Wrist	Single	1min	-	E_v, R, G, B, mEDI	Raw
Liu *et al.*[67]	63	Cancer patients	Actillume	Wrist	Single	-	-	E_v	-
Lowden *et al.*[68]	32	Office-workers	MotionWatch 8	Wrist	Single	1min	-	E_v	Raw
Maren *et al.*[69]	28	Young adults	Actiwatch Spectrum	Upper arm	Tandem	1min	Art.	E_v, B	Raw
Martin *et al.*[70]	28	Schizophrenia patients	Actillume	Wrist	Single	1min	-	E_v	-
Martin *et al.*[71]	88	Students	Actiwatch-L	Wrist	Single	1min	Art.	E_v	Raw
Martin *et al.*[72]	57	Students	Actiwatch-L	Wrist	Single	30s	Art.	E_v	Raw
Martinez-Nicolas *et al.*[73]	88	Students	HOBO Pendant	Chest	Tandem	30s	Nat.	E_v	Raw
Martinez-Nicolas *et al.*[74]	131	Students	HOBO Pendant	Chest	Tandem	30s	Nat.	E_v	Raw
Nioi *et al.*[75]	20	Elderly	Actiwatch Spectrum	Chest	Tandem	15s	-	E_v, B	-
Obayashi *et al.*[76]	192	Eldery	Actiwatch 2	Wrist	Single	1min	-	E_v	Aggr.
Obayashi *et al.*[77]	192	Eldery	Actiwatch 2	Wrist	Single	1min	-	E_v	Aggr.
Okudaira *et al.*[10]	10	General	Custom	Eye, Wrist	Tandem	5min	-	E_v	-
Papantoniou *et al.*[78]	117	Shift-workers	HOBO Pendant	Chest	None	15s	-	E_v	-
Pattinson *et al.*[79]	48	Children	Actiwatch 2	Wrist	Single	1min	-	E_v	-
Peeters *et al.*[12]	20	Office-workers	Lightlog	Chest	None	3min	Art.	E_v	Raw
Phillips *et al.*[80]	22	Students	MotionLogger-L	Wrist	Single	1min	Art.	E_v	-
Phillips *et al.*[13]	56	General pop.	Actiwatch 2, Actiwatch-L, Actiwatch Spectrum, Actiwatch Plus	Wrist	Single	1min	-	E_v	-
Price *et al.*[81]	40	Shift-workers	Actiwatch Spectrum	-	Single	-	Art.	mEDI, B	-
Rabstein *et al.*[82]	100	Shift-workers	LightWatcher	Upper arm	Single	10s	-	E_v, B	Raw

(*Continued*)

Table A1.1. (Continued)

Authors	N	Sample	Dosimeter	Position	Actigraphy setup	Recording interval	Calibration	Quantities	Log-transformation
Rea *et al.*[83]	58	Teachers	Daysimeter	Eye	Single	-	No descr.	E_v, CS	-
Read *et al.*[17]	112	Children	HOBO Pendant, Actiwatch 2	Chest, Wrist	None	5min, 30s	-	E_v	-
Refinetti *et al.*[84]	1887	Hispanic, Latino	Actiwatch Spectrum	Wrist	Single	30s	-	E_v, R, G, B	-
Reid *et al.*[85]	54	General pop.	Actiwatch-L	Wrist	Single	2min	-	E_v	-
Rufiange *et al.*[86]	25	Indoor-, Outdoor-workers	Actiwatch-L	-	Single	-	-	E_v	Raw
Ruiz *et al.*[87]	76	General pop.	ActTrust	Wrist	Single	1min	-	E_v	-
Savides *et al.*[11]	10	General pop.	Custom	Eye, Wrist	None	5min	-	E_v	
Scheuermaier *et al.*[88]	44	General pop.	Actiwatch-L	Wrist	Single	1-2min	-	E_v	Aggr.
Silva *et al.*[89]	12	Students	Geneactiv	Wrist	Single	1min	-	E_v	-
Smit *et al.*[90]	91	Indigenous	Actiwatch 2	Wrist	Single	-	-	E_v	-
Shochat *et al.*[91]	77	Eldery	Actillume	Wrist	Single	1min	-	E_v	-
Shochat *et al.*[92]	19	Students	Actiwatch-L	Wrist	Single	1min	-	E_v	Raw
Smolders *et al.*[93]	42	University staff, Students	Daysimeter	Eye	None	30s	-	E_v, CS	Aggr.
Staples *et al.*[94]	23	Eldery	Actiwatch-L (CamNtech)	Wrist	Single	1min	-	E_v	Raw
Stone *et al.*[95]	25	Shift-workers	Actiwatch Spectrum	Wrist	Single	1min	-	E_v	Raw
Stothard *et al.*[96]	5	General pop.	Actiwatch Spectrum	Wrist	Single	1min	-	E_v, R, G, B	-
Sun *et al.*[97]	163	Cancer patients	Actiwatch-L	Wrist	Single	-	-	E_v	-
te Lindert *et al.*[98]	35	Insomnia patients	Dimesimeter	Chest	None	1min	-	CS	-
Thorne *et al.*[99]	17	Shift-workers	Actiwatch-L (CamNtech)	-	Single	1min	-	E_v	-
Thorne *et al.*[100]	34	General pop.	Actiwatch RGB, Actiwatch-L (CamNtech)	Wrist	Single	2min	-	E_v, R, G, B	-
Tsai *et al.*[101]	22	Mothers, Infants	Actiwatch-L	Wrist, Ankle	Tandem	30s	-	E_v	Raw
Tsai *et al.*[102]	26	Infants	Actiwatch-L	Ankle	Single	30s	-	E_v	Raw
Tsuzuki *et al.*[103]	8	Elderly	Actiwatch-L	Wrist	Single	1min	-	E_v	-
Ulaganathan *et al.*[16]	61	Adolescents, Children	Actiwatch 2	Wrist	Single	30s	-	E_v	-
Ulset *et al.*[104]	49	Children	Actiwatch 2	Wrist	Single	1min	-		Raw
van Duijnhoven *et al.*[105]	62	Office-workers	Lightlog	Chest	None	5min	Art.	E_v, B, CCT	-
Vinzio *et al.*[106]	10	Eldery	Actiwatch-L (CamNtech)	Wrist	Single	-	-	E_v	-
Wallace-Guy *et al.*[107]	154	Postmenop- women	Actillume	Wrist	Single	-	-	E_v	-
Wams *et al.*[108]	20	General	MotionWatch 8	Wrist	Single	1min	-	E_v	Raw
Wang *et al.*[109]	37	Postpart. women	Actillume	Wrist	Single	1min	-	E_v	Raw
Wilson *et al.*[110]	24	DSPD patients	Actiwatch-L	Wrist	Single	-	-	E_v	-
Woelders *et al.*[111]	20	General pop.	MotionWatch 8	Wrist	Single	1min	-	E_v	Raw
Wright *et al.*[112]	8	General pop.	Actiwatch-L	Wrist	Single	-	-	E_v	-
Youngsted *et al.*[113]	459	Postmenop. women	Actillume	Wrist	Single	-	No descr.	E_v	Aggr.
Zeitzer *et al.*[14]	31	Insomnia patients	Actiwatch-L	Wrist	Single	-	-	E_v	-

Note: E_v = Illuminance, mEDI = melanopic equivalent daylight illuminance, R = long-wavelength irradiance, G = medium-wavelength irradiance, B = short-wavelength irradiance, M = irradiance at 450-500nm, E_c = Irradiance weighted by $c(\lambda)$[114], CLA = Circadian Light, CS = Circadian Stimulus, CCT = correlated color temperature, Nat. = naturalistic, Art. = artificial, Aggr. = aggregated data. Empty cells with a hyphen indicate that no information was reported.