OSF Preregistration

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Light exposure and light behaviour differences between Malaysia and Switzerland

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Subject
Life Sciences: Neuroscience and Neurobiology: Behavioral Neurobiology
Medicine and Health Sciences: Medical Sciences: Neurosciences
Medicine and Health Sciences: Medical Specialties: Sleep Medicine
Social and Behavioral Sciences: Psychology: Other Psychology
Social and Behavioral Sciences: Psychology: Health Psychology Social and Behavioral Sciences: Psychology: Human Factors Psychology
Social and Behavioral Sciences: Science and Technology Studies

Background information

Light is the main entrainment agent synchronizing human circadian rhythms to the natural light-dark rhythm (Foster et al., 2020). Since the invention of electrical light, our daily pattern of light exposure has rapidly altered from this robust cycle to a chaotic one, emerging from an incalculable combination of artificial lights around us and our behaviour around lights. Disrupting the entrainment of endogenous circadian rhythms by disordered light patterns can cause various diseases (e.g., Ansu Baidoo & Knutson, 2023; Fishbein et al., 2021; Roenneberg & Merrow, 2016). As prior light history plays a role in our subsequent sensitivity for light (Hébert et al., 2002), recommendations for healthier light behaviour strongly depend on light exposure during day and night. Analysing light exposure behaviour is therefore the start to restoring order, to both mitigate the negatives and increase the benefits. To this end, the Light Exposure Behaviour Assessment LEBA (Siraji et al., 2023), a novel subjective tool was developed that categorises light exposure-related behaviours into five broad categories based on participant's retrospective recall of the past four weeks.

The main objective of this project is to investigate differences in objectively measured (using the SPECCY dosimeter) and subjectively measured (using the LEBA questionnaire) light exposure in a site in Malaysia compared to a site in Switzerland. Additionally, the accuracy of LEBA in categorising people's behaviour by coupling the scores of LEBA with the readings from the wearable dosimeter SPECCY (Mohamed et al., 2021) will be explored. The chest-worn wearable dosimeter outputs visual and non-visual metrics of light exposure following relevant CIE (The International Commission on Illumination) standards via a full spectral reconstruction. Light exposure can be logged at a minimum interval of 15 seconds. LEBA's accuracy in categorising people's behaviour

based on a retrospective recall will be validated against objective measurements of light exposure.

The following research questions are addressed in this study:

RQ 1: Are there differences in objectively measured light exposure between the two sites, and if so, in which light metrics?

RQ 2: Are there differences in self-reported light exposure patterns using LEBA across time or between the two sites, and if so, in which questions/scores?

RQ 3: In general, how are light exposure and LEBA related and are there differences in this relationship between the two sites?

Study Information

Hypotheses

For RQ 1, the following hypotheses will be addressed:

- **H1:** There are differences in light logger-derived light exposure intensity levels and duration of intensity between Malaysia and Switzerland.
- **H0:** No differences between Malaysia and Switzerland.

- **H2:** There are differences in light logger-derived timing of light exposure between Malaysia and Switzerland.
- **H0:** No differences between Malaysia and Switzerland.

For RQ 2, the following hypotheses will be addressed:

- **H3:** There are differences in LEBA items and factors between Malaysia and Switzerland.
- **H0:** No differences between Malaysia and Switzerland.

- **H4:** LEBA scores vary over time within participants.
- **H0:** No differences between Malaysia and Switzerland.

For RQ 3, the following hypotheses will be addressed:

- **H5:** LEBA items correlate with preselected light-logger derived light exposure variables.
- **H0:** No correlation.

- **H6:** There is a difference between Malaysia and Switzerland on how well light-logger derived light exposure variables correlate with subjective LEBA items.
- **H0:** No differences between Malaysia and Switzerland.

For an overview of research questions, hypotheses and statistical tests addressing the hypotheses see **Table 4**.

Design Plan

Study type

This is an observational study. Data were collected from study participants who were not randomly assigned to a treatment.

Blinding

No blinding was implemented in this study.

Randomisation

No randomisation was employed in this study, as all participants in both sites completed in the same protocol.

Study design

This pre-registration concerns a previous data collection. Data were collected in Malaysia and Switzerland. For each participant at both sites, the experiment lasted for a month. Day 0 and day 31 mainly involved the collection and returning of equipment, while days 1 – 30 involved the collection of light and questionnaire data from the participants (**Figure 1.**). Light data were collected via a neck-worn portable light dosimeter (SPECCY), and questionnaires were deployed online via Qualtrics (Malaysia) and REDCap (Switzerland). On day 0, participants collected the dosimeter and filled in the Pittsburgh Sleep Quality Index (PSQI) questionnaire. Data collection for each participant commenced once they had collected their light loggers and detailed instructions were given.

SPECCY was worn around the neck at chest-level, 20 cm below the wearer's chin with the sensing area positioned such that it faces outwards, in the line of sight of light incident on the wearer's eyes. From day 1 to day 14, participants always wore SPECCY with the exclusion of when the participant would be exposed to high amounts of water (e.g., bath, swimming) or when the dosimeter was being charged. Participants were asked to charge the sensor daily for an hour. This charging time was chosen by the participants themselves, but it was recommended that this charging time remained consistent throughout the experiment and preferably at a time when the participants were mostly sedentary. Participants were also instructed to ensure that the sensor area of SPECCY was not covered by any obstacles or objects (e.g., hands, hair, seatbelts, etc.). The

position of SPECCY when participants were asleep did not matter. When SPECCY was not worn (e.g., when participants were taking baths or SPECCY was being charged), participants were instructed to place SPECCY such that its sensor area was blocked (i.e. sensor area would not detect any light). During these 2 weeks, participants were asked to answer the LEBA questionnaire twice a week as instructed, before going to bed at night. On day 15, the light dose data recorded by SPECCY was downloaded. For the remainder of the experiment (day 15 to day 30), participants continued wearing SPECCY following the same routine as the period from day 1 to day 14. Similarly, they were asked to answer the LEBA questionnaire twice a week as instructed, before going to bed at night. On day 31, participants returned SPECCY, and the collected light dose data was downloaded. Data collection completed after they answer the Pittsburgh Sleep Quality Index (PSQI) questionnaire.

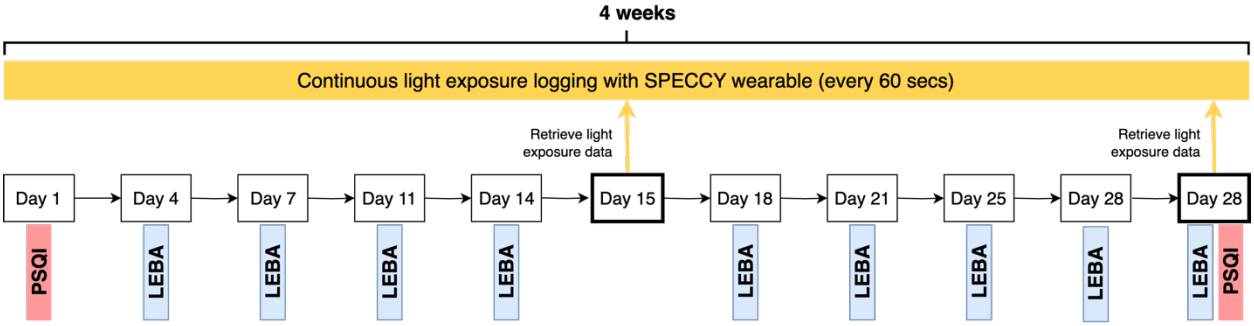

Figure 1. Overview of the study design. Abbreviations: PSQI, Pittsburgh Sleep Quality Index; LEBA, Light Exposure Behaviour Assessment.

Sampling Plan

This pre-registration concerns a previous data collection. 20 and 19 participants were recruited to participate in the data collection experiment in Switzerland and Malaysia respectively. Participants were recruited based on the following inclusion criteria:

1. Age of 19 – 65 years old
2. No history of drug abuse
3. Caffeine consumption < 2 cups per day
4. Alcohol consumption < 2 drinks per day or 14 drinks a week
5. Smoke < 2 cigarettes per day

Existing data

Registration prior to analysis of the data: As of the date of submission, the data existed and were accessed, though no formal analysis had been conducted related to the research plan (including calculation of summary statistics).

Explanation of existing data

Data had been collected at the two different sites prior to this preregistration. Data were subsequently viewed to understand potential (amount of) missing data and reasons for missing data as well as to understand data structure. Author J.Z. was not involved in data collection procedures.

A subset of data were pre-analysed in the following ways by J.Z.:

- Import of light logging and questionnaire data R statistical software and the LightLogR package (Zauner et al., 2024)
- Calculation and visualisation of timespan of data collection, missing observations, and observation intervals
- Visual inspection for implausible light values
- Calculation of two example metrics (Mean timing of light above 250 lx melanopic EDI; time of light above 250 lx melanopic EDI)
- Visualisation of a correlation matrix of LEBA item data with the example metrics
- Visualisation of melanopic EDI for an average day across all participants and days for each site, as a double plot

These pilot analyses are not expected to bias the subsequent analyses.

Data collection procedures

Data collection took place in two sites, one in University of Basel, Switzerland (47.5585° N, 7.5839° E) and one in Monash University, Malaysia (3.0650° N, 101.6009° E). Data collection in Switzerland was carried out from July – October (2023), while data collection in Malaysia was carried out from November – December (2023). Participants stayed within a 50 km radius of the respective University sites.

For participants in Malaysia, applicants had to fill in an application form that was implemented using Google forms which asked questions relevant to the inclusion/exclusion criteria. A total of 50 applicants were registered. 14 applicants did not meet the inclusion criteria, and the remaining applicants were either accepted, declined participation, or not contacted. One person was excluded from the analysis due to a lost SPECCY device. Qualtrics links to the LEBA and PSQI questionnaires were sent to the participants according to their schedules and they would fill in the questionnaires via the link.

Participants in Switzerland were recruited through an online advertisement posted on the University's bulletin board. The ad included a brief description of the study and inclusion and exclusion criteria. Those who expressed interest in the study were contacted via

email to verify their eligibility. Upon confirmation, they were provided with a detailed study information sheet. Eligible and interested applicants were scheduled for a visit at the lab on a Monday. On site participants were briefed in person about the study and registered using Qualtrics. Participants also completed the PSQI on site using their personal phones and received instructions on the SPECCY device.

Wearable light logger

A wearable light logger, SPECCY, was used for data collection in Malaysia and Switzerland. The light logger, modified from the light spectral sensor by Mohamed et al. (2021) and developed at Monash University Malaysia's Intelligent Lighting Laboratory (MMILL), captures spectral information across the visible range of 380 nm to 780 nm. SPECCY has been validated by the Australian Photometry and Radiometry Laboratory and has an effective measuring range from 1 lx to 130,000 lx. The light sensing system is constructed from a combination of three multi-channel sensors, which together provide a total of 14 optical sensing channels within the measurement range and four channels in the infrared (IR) range. Through proprietary software layers, these channels capture low-resolution spectral data adjusted for sensor saturation and baseline signal calibration. Incorporated within a compact printed circuit board (PCB), the device houses the three multi-channel sensors, optimally placed for temperature consistency, an ambient temperature sensor, a microprocessor enabling Bluetooth Low Energy connectivity, 16 MB of onboard flash storage allowing for over 130,000 spectral measurements, vital indicators and controls such as LEDs and a connectivity toggle button, and a micro-USB charging port. All of these are securely encased within a 3D printed housing made of PLA material. Finally, enhanced sensor directional response is ensured by a cosine corrector built into the case.

Figure 1. Picture of the Mini Spectral Sensor SPECCY light logger. Manufactured by Monash University's Intelligent Lighting Laboratory. Picture used with permission.

Surveys

LEBA

The Light Exposure Behaviour Assessment (LEBA; Siraji et al., 2023) tool was developed to examine how light exposure behaviours affect health and well-being. LEBA categorises five key behaviours: wearing blue light filtering glasses indoors and outdoors (Factor 1), spending time outdoors (Factor 2), using phones and smartwatches in bed before sleep (Factor 3), controlling and using ambient light before bedtime (Factor 4), and using light in the morning and during daytime (Factor 5).

PSQI

The Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1989) is a self-report questionnaire that assesses sleep quality over a one-month period. It measures seven components, including sleep duration, disturbances, and daytime dysfunction, and produces a global score. In studies of healthy and clinical patients, the PSQI has shown good reliability and validity with a Cronbach's α of.83 in the original publication. A global score greater than 5 accurately discriminates between good and poor sleepers.

Sample size

Participants in Switzerland consisted of 5 males and 15 females (age 31.35 ± 9.66 years old), and all participants completed their data collection successfully.

In Malaysia, one participant failed to complete the experiment. Eight males and 11 females (age 24 ± 6.74 years old) completed data collection successfully.

Sample size rationale

No specific sample size was calculated for the study and was based on convenience sampling and resource limitations.

Stopping rule

No specific stopping rule was implemented.

Variables

Measured variables

SPECCY-derived variables

Light data from the SPECCY device (melanopic EDI) will be analysed using the R package *LightLogR* (Zauner et al., 2024) to derived relevant variables. For an overview of calculated light variables see **Table 1**. For an exact calculation equation for each metric see https://github.com/tscnlab/LightLogR.

Call to calculate metric	Light metric name	Description
barroso_lighting_metrics()	Circadian lighting metrics (Barroso et al., 2014)	Calculates the metrics proposed by Barroso et al. (2014) for light-dosimetry in the context of research on the non-visual effects of light
bright_dark_period()	Brightest or darkest continuous period	Finds the brightest or darkest continuous period of a given timespan and calculates its mean light level, as well as the timing of the period's onset, midpoint, and offset. It is defined as the period with the maximum or minimum mean light level. Note that the data need to be regularly spaced (i.e., no gaps) for correct results
centroidLE()	Centroid of light exposure	Calculates the centroid of light exposure as the mean of the time vector weighted in proportion to the corresponding binned light intensity
disparity_index()	Disparity index	Calculates the continuous disparity (Fernández-Martínez et al., 2018)
duration_above_threshold()	Duration above/below threshold or within threshold range	Calculates the duration spent above/below a specified threshold light level or within a specified range of light levels
exponential_moving_average()	Exponential moving average filter (EMA)	Smoothes the data using an exponential moving average filter with a specified decay half-life
frequency_crossing_threshold()	Frequency of crossing light threshold	Calculates the number of times a given threshold light level is crossed
intradaily_variability()	Intradaily variability (IV)	Calculates the variability of consecutive light levels within

		a 24h day. Calculated as the ratio of the variance of the differences between consecutive light levels to the total variance across the day. Calculated with mean hourly light levels. Higher values indicate more fragmentation
interdaily_stability()	Interdaily stability (IS)	This function calculates the variability of 24h light exposure patterns across multiple days. Calculated as the ratio of the variance of the average daily pattern to the total variance across all days. Calculated with mean hourly light levels. Ranges between 0 (Gaussian noise) and 1 (Perfect Stability)
midpointCE()	Midpoint of cumulative light exposure.	Ccalculates the timing corresponding to half of the cumulative light exposure within the given time series
nvRC()	Non-visual circadian response	Calculates the non-visual circadian response (nvRC). It takes into account the assumed response dynamics of the non-visual system and the circadian rhythm and processes the light exposure signal to quantify the effective circadian-weighted input to the non-visual system
nvRC_circadianDisturbance() nvRC_circadianBias() nvRC_relativeAmplitudeError()	Performance metrics for circadian response	These functions compare the non-visual circadian response for measured personal light exposure to the nvRC for a reference light exposure pattern, such as daylight
nvRD()	Non-visual direct response	Calculates the non-visual direct response (nvRD). It takes into account the

		assumed response dynamics of the non-visual system and processes the light exposure signal to quantify the effective direct input to the non-visual system
nvRD_cumulative_response()	Cumulative non-visual direct response	Calculates the cumulative non-visual direct response (nvRD). This is basically the integral of the nvRD over the provided time period in hours. The unit of the resulting value thus is "nvRD*h"
period_above_threshold()	Length of longest continuous period above/below threshold	Length of the longest continous period above/below a specified threshold light level or within a specified range of light levels
pulses_above_threshold()	Pulses above threshold	Clusters the light data into continuous clusters (pulses) of light above/below a given threshold
threshold_for_duration()	Find threshold for given duration	Threshold for which light levels are above/below for a given duration. This function can be considered as the inverse of duration_above_threshold
timing_above_threshold()	Mean/first/last timing above/below threshold.	Mean, first, and last timepoint (MLiT, FLiT, LLiT) where light levels are above or below a given threshold intensity within the given time interval

Table 1. Overview of objectively derived outcome variables from light logging data and their calculations.

LEBA-derived variables

The Light Exposure Behaviour Assessment (LEBA; Siraji et al., 2023) captures light exposure-related behaviours on a 5-point Likert type scale ranging from 1 to 5 (1 = never;

2 = rarely; 3 = sometimes; 4 = often; 5 = always). The score of each factor is calculated by the summation of scores of items belonging to the corresponding factor (**Table 2**). Respondents are requested to respond to each item in a retrospective manner where they try to capture their propensity of different light exposure related behaviours. Originally, this covers the past 4 weeks but was amended in the current study to "past 3-4 days" (asked twice per week) for the Basel site (the original framing of 4 weeks was kept for the Malaysian site). For a list of all LEBA items, see **Table 5.**

Factor name	Score
F1: Wearing blue light filters	01+02+03
F2: Spending time outdoors	04(R)+05+06+07+08+09
F3: Using phone and smartwatch in bed	10+11+12+13+14
F4: Using light before bedtime	15+16+17+18
F5: Using light in the morning and during daytime	19+20+21+22+23

Table 2. Scoring of Light Exposure Behaviour Assessment (LEBA) items. Note that R denotes items that are reversed-scored. F1-F5 denotes the calculated Factors.

Indices

For the LEBA, five factors will be calculated based on individual LEBA items (see **Table 2**). In scoring the PSQI, seven component scores are derived, each scored 0 (no difficulty) to 3 (severe difficulty). The component scores are summed to produce a global score (range 0 to 21). Higher scores indicate worse sleep quality, with a score >5 suggesting significant sleep difficulties (see **Table 3**).

Component	Question (Q)	Component Score
(1) Subjective sleep quality	#6	0-3
(2) Sleep latency	#2 #5a	Sum of Q2 (0-3)+Q5a (0-3): If 0 → 0 1-2 → 1 3-4 → 2 5-6 → 3
(3) Sleep duration	#4	0-3
(4) Habitual sleep efficiency (Sleep efficiency = hours slept / hours in bed) X 100%)	#1 #3 #4	If >85% → 0 75-84% → 1 65-74% → 2 <65% → 3
(5) Sleep disturbance	#5b-5j	Sum of Q5b (0-3) to Q5 (0-3): If 0 → 0

		1-9 → 1 10-18 → 2 19-27 → 3
(6) Use of sleep medication	#7	0-3
(7) Daytime dysfunction	#8 #9	Sum of Q8 (0-3) +Q9 (0-3: If 0 → 0 1-2 → 1 3-4 → 2 5-6 → 3
Global PSQI Score		**Sum of Components 1-7**

Table 3. Scoring of Pittsburgh Sleep Quality Index (PSQI) items.

Analysis Plan

Descriptive statistics and statistical models

RQ #	**Hypothesis**	**Variable(s)**	**Statistical test(s)**	**Wilkinson Formula** (if appropriate)
1	**H1:** There are differences in light logger-derived light exposure **intensity levels** and **duration** of intensity between Malaysia and Switzerland. **H0:** No difference.	Intensity level light metrics - TAT250 - TAT1000 - Period above threshold 1000 - TAT250 (daytime hours) - TBT10 (evening hours)	Generalized mixed-effect analyses on the effect of site on various light parameters 5 Models	$\text{metric} = \text{site} + (1\|\text{site:participant})$
	H2: There are differences in light logger-derived **timing of light** exposure between Malaysia and Switzerland.	Timing light metrics - M10m - L5m - IS - IV - LLiT 10 - LLit 250 - Frequency crossing threshold	Generalized mixed-effect model (GAMM) on the effect of site on various parameters 7 models	$\text{metric} = \text{site} + (1\|\text{site:participant})$

	H0: No difference.	Time-of-day (two-level factor: daytime / evening) Melanopic EDI	Linear mixed-effect model on the interaction of time-of-day and site on melanopic EDI	$\text{melEDI} = \text{site} \cdot \text{time-of-day} + (1 + \text{time-of-day} \mid \text{site:participant})$
		Time-of-day (seco from midnight) Melanopic EDI	Generalized mixed-effect model (GAMM) on the interaction of time-of-day and site on melanopic EDI	$\text{melEDI} = s(\text{time-of-day, site}) + s(\text{time-of-day, by = participant}) + s(\text{participant, by = site})$ Note on GAMM basis splines for smooth (*s()*) terms: 1. cyclic spline (cs), factor spline (fs) 2. cyclic spline (cs) 3. random effect (re)
2	**H3:** There are differences in LEBA items and factors between Malaysia and Switzerland. **H0:** No difference.	- all individual LEBA items (**Table 5**) - all 5 LEBA Factors (**Table 2**)	Cumulative link mixed-effect analyses on the effect of site on each LEBA question and factor 23 + 5 models	$\text{LEBA item/factor} = \text{site} + (1 \mid \text{site:participant})$
	H4: LEBA scores vary over time within participants **H0:** no variance	- all individual LEBA items (**Table 5**) - all 5 LEBA Factors (**Table 2**)	Bootstrap analysis of the standard deviation of LEBA scores within participants for the Malaysia dataset 23 + 5 bootstraps	
3	**H5:** LEBA items correlate with pre-selected light logger-derived light exposure variables. **H0:** No correlation.	See **Table 5** for all relevant variables.	Correlation matrix with one matrix per site. 2x85 correlations	

	H6: There is a difference between Malaysia and Switzerland on how well light logger-derived light exposure variables correlate with subjective LEBA items. **H0:** No difference between Malaysia and Switzerland.	See **Table 5** for all relevant variables.	Generalized mixed-effect analyses to determine the effect of site on the dependency between light exposure metrics and LEBA items/factors 23 + 5 models	$\text{metric} = \text{site} \cdot \text{LEBA item/factor} + (1\|\text{site:participant})$

Table 4. Overview of research questions, hypotheses and statistical tests to address the hypotheses. Abbreviations: GAMM, Generalized additive mixed-effect model; H0, Null hypothesis; H1, Hypothesis 1; IS, Interdaily Stability; IV, Intradaily variability; LEBA, Light Exposure Behaviour Assessment; LLiT, Last time above threshold; LLiT 10, Low light intensity threshold at 10 lux; LLiT 250, Low light intensity threshold at 250 lux; L5m, Mean across darkest 5 hours; M10m, Mean across brightest 10 hours; melEDI, Melanopic equivalent daylight illuminance; RQ, Research question; TAT250, Time above threshold 250 lux; TAT1000, Time above threshold 1000 lux; TBT10, Time below threshold 10 lux.

We also test if light exposure and LEBA items are related (**RQ3**) by calculating specific light variables using the R package *lightlogR* and correlate them to the respective LEBA item. See **Table 5** for an overview of which light variables will be calculated for each LEBA item.

LEBA Item	**LEBA Question**	**List of calculated light variables**
1	I wear blue-filtering, orange-tinted, and/or red-tinted glasses indoors during the day.	NA
2	I wear blue-filtering, orange-tinted, and/or red-tinted glasses outdoors during the day.	NA
3	I wear blue-filtering, orange-tinted, and/or red-tinted glasses 1 hour before attempting to fall asleep.	NA
4	I spend 30 minutes or less per day (in total) outside.	['M10', 'TAT250', 'TAT1000', 'Period above threshold 1000', 'IV', 'IS']
5	I spend between 30 minutes and 1 hour per day (in total) outside.	['M10', 'TAT250', 'TAT1000', 'Period above threshold 1000', 'IV', 'IS']
6	I spend between 1 and 3 hours per day (in total) outside.	['M10', 'TAT250', 'TAT1000', 'Period above threshold 1000', 'IV', 'IS']

7	I spend more than 3 hours per day (in total) outside.	['M10', 'TAT250', 'TAT1000', 'Period above threshold 1000', 'IV', 'IS']
8	I spend as much time outside as possible.	['M10', 'TAT250', 'TAT1000', 'Period above threshold 1000', 'IV', 'IS']
9	I go for a walk or exercise outside within 2 hours after waking up.	['first time above threshold of 1000 (FLitT 1000)', 'IV', 'IS']
10	I use my mobile phone within 1 hour before attempting to fall asleep. + 15 + 16	['last time above threshold of 10 (LLiT 10)', 'last time above threshold of 250 (LLiT 250)', 'L5 (without sleep period)', 'IV', 'IS']
13	I look at my smartwatch within 1 hour before attempting to fall asleep.	['last time above threshold of 10 (LLiT 10)', 'last time above threshold of 250 (LLiT 250)', 'L5 (without sleep period)', 'IV', 'IS']
11	I look at my mobile phone screen immediately after waking up.	['first time above threshold of 250 (FLitT 250)', 'IV', 'IS']
12	I check my phone when I wake up at night.	['L5', 'IV', 'IS']
14	I look at my smartwatch when I wake up at night.	['L5', 'IV', 'IS']
15	I dim my mobile phone screen within 1 hour before attempting to fall asleep.	['last time above threshold of 10 (LLiT 10)', 'last time above threshold of 250 (LLiT 250)', 'L5 (without sleep period)', 'IV', 'IS']
16	I use a blue-filter app on my computer screen within 1 hour before attempting to fall asleep.	['last time above threshold of 10 (LLiT 10)', 'last time above threshold of 250 (LLiT 250)', 'L5 (without sleep period)', 'IV', 'IS']
17	I use as little light as possible when I get up during the night.	['L5 and L5 (only night)', 'IV', 'IS']
18	I dim my computer screen within 1 hour before attempting to fall asleep.	['last time above threshold of 10 (LLiT 10)', 'last time above threshold of 250 (LLiT 250)', 'L5 (without sleep period)', 'IV', 'IS']
19	I use tunable lights to create a healthy light environment.	['IV', 'IS', 'L5 (with/without night)', 'M10']
20	I use LEDs to create a healthy light environment.	['LE', 'Spectral contribution', 'Melanopic/photopic ratio']
21	I use a desk lamp when I do focused work.	['LE']
22	I use an alarm with a dawn simulation.	['Spectral contribution', 'first time above threshold of 10 (FLitT 10)', 'first time above threshold of 250 (FLitT 250)']
23	I turn on the lights immediately after waking up.	['Spectral contribution', 'first time above threshold of 10 (FLitT 10)', 'first time above threshold of 250 (FLitT 250)']

Table 5. List of Light Exposure Behaviour Assessment (LEBA) items and corresponding objectively derived light variables from light logging data. Abbreviations: FLitT 10, First time above threshold of 10 lux; FLitT 250, First time above threshold of 250 lux; FLitT 1000, First time above threshold of 1000 lux; IS, Interdaily Stability; IV, Intradaily Variability; LE, Light Exposure; L5, Mean across darkest 5 hours; L5 (only night), Mean across darkest 5 hours during the night; LLiT 10, Last time above threshold of 10 lux; LLiT 250, Last time above threshold of 250 lux; M10, Mean across brightest 10 hours; Melanopic/photopic ratio, Ratio between melanopic and photopic illuminance; Period above threshold 1000, Time above the threshold of 1000 lux; Spectral contribution, Contribution of specific spectral ranges (e.g., blue light); TAT250, Time above threshold of 250 lux; TAT1000, Time above threshold of 1000 lux.

Exploratory analyses

In a secondary analysis, we go beyond the specified hypotheses described above. Since we expect differences between the two sites in terms of objectively measured light exposure (using the SPECCY light logger; **RQ1**) and subjectively measured light exposure (using the LEBA questionnaire; **RQ2**)**,** we also want to test this thoroughly in a data-driven way. To this end, we will do cross correlation of all available light metrics in *LightLogR* for the objectively measured light exposure with all available variables and factors from the LEBA questionnaire across sites.

Transformations of variables

LEBA-derived variables

Item 4 of the LEBA questionnaire needs to be re-versed scored for the F2 calculation. See section “Variables” for more information on items and factors of the LEBA.
LEBA scores are stored dummy coded in the Switzerland dataset (exported from RedCap), where 1 to 5 encode “Never”, “Rarely”, “Sometimes”, “Often”, and “Always”, respectively. In the Malaysia dataset (exported from Qualtrix), answers are directly coded. Upon import, all LEBA scores are converted to factors that are dummy-coded as described for the Switzerland dataset.

Melanopic EDI-derived variables

The time series of melanopic EDI (in lx) are the base measurement used. Several metrics are calculated from that measure (see **Table 1**), besides the mean. The period over which these metrics are calculated varies, however, depending on the specific research question, hypothesis, and metric. Generally, metrics are calculated per participant and day, except interdaily stability and intradaily variability, which are calculated per participant.
Whenever melanopic EDI is directly used in a statistical model, it will be logarithmically transformed with a base of 10.

Time-of-Day

For some research questions, the distinction of daytime vs. evening time or nighttime is relevant when calculating metrics, as either time-of-day is a part of the statistical model, or only a portion of the day is relevant. In those cases, metrics are calculated based on a filtered time series of melanopic EDI. These filters have three thresholds: sunrise, sunset, and midnight. Sunrise and sunset are calculated based on latitude, longitude (Switzerland (47.5585° N, 7.5839° E), Malaysia (3.0650° N, 101.6009° E)), and calendar date with the {suntools} package (Bivand & Luque, 2023). Sunrise to sunset is considered daytime, sunset to midnight as evening, and sunset to sunrise as nighttime.

Datetimes

Time-series data are exported in local time by the SPECCY device. Upon import in R these are stored as the POSIXct class by *LightLogR*, which stores times in seconds beginning with 1 January 1970. The sites are in different time zones. Thus, directly including the datetime variable in a statistical model or a combined visualisation is not sensible, as we are interested in differences depending on local time, not real-time differences due to time zones. When only the local clock time is of interest, i.e., the date can be disregarded, datetime is transformed into seconds from midnight local time. When the local time, including date, is of interest, the datetime is transformed by overwriting the time zone of both sites to UTC, thus forcing them to operate on the same timeline. Depending on the research questions, data may be aggregated depending on datetimes, e.g., to display hourly values in a figure. Aggregation will always use the mean value within the aggregation window, and aggregations will be clearly stated alongside results.

Correlating LEBA scores with light exposure metrics

Depending on the site, the correlation analysis (**H4**) uses different timespans due to how the items in the questionnaire were framed.

For Switzerland, where the LEBA asked about the behaviour in the current respective period (i.e., about the past three or four days), light exposure metrics will be calculated from the timespans between each LEBA questionnaire. These metrics will be correlated with the respective LEBA scores. For example, LEBA scores from day 7 will be correlated with light exposure metrics from days 5 to 7, as the prior LEBA questionnaire was collected at the end of day 4. All other time spans between assessments are calculated accordingly.

For Malaysia, where the LEBA asked about the behaviour in the past four weeks, light exposure metrics will be calculated for the whole four weeks of data collection and correlated with the final round of LEBA scores collected on day 31.

For light exposure metrics that are calculated for each day, an average value is calculated prior to correlation. This avoids a one-to-many comparison (one LEBA datapoint to many light exposure metric datapoints) that would skew significance tests of the correlation.

Inference criteria

Check for assumptions

Appropriate model diagnostics will be performed for all statistical tests to ensure linearity of (generalized) relationship, normally distributed residuals and random effects, and homoscedastic residuals. In the case of generalized additive models, the number of knots (k) will be tested to ensure sufficient degrees of freedom to adequately capture the nonlinear relationships.

Statistical tests

Table 4 links specific statistical tests to the research questions and hypotheses. Overall, one of five statistical model types is used:

1. (Generalized) linear mixed-effect models for continuous numeric dependent variables, using the lmer() and glmer() functions in the {lme4} (version 1.1-35.5) package (Bates et al., 2015). Generally, a Gaussian error distribution is assumed for dependent variables. Depending on the type and distribution of the parameter in question, a fitting error distribution will be used, such as binomial or beta.
2. Cumulative link mixed-effect models for ordinal dependent variables, using the clmm() function in the {ordinal} (version 2023.12-4.1) package (Christensen, 2010).
3. Generalized additive mixed-effect models for non-linear relationships, using the gam() and bam() functions in the {mgcv} (version 1.9-1) package (Wood, 2000)
4. Correlation matrices using Spearman-rank correlation for the correlation of continuous numeric and ordinal variables. These models use the cor() function in the {stats} (version 4.4.0) package in base R (R Core Team, 2021), the rcorr() function in the {Hmisc} (version 5.1-3) package (Harrell, 2003), and the pairwise_cor() function in the {widyr} (version 0.1.5) package (Robinson & Silge, 2022).
5. Bootstrapping to determine 95% confidence intervals for variables. Bootstrapping will be performed with base R functions such as sample() and the {tidyverse} (version 2.0.0) packages (Wickham, 2016; Wickham et al., 2019).

Latest version of packages might be used at the time of analysis.

Accounting for multiple testing

For every hypothesis, a false-discovery-rate correction (Benjamini-Hochberg) will be applied based on the number of models/tests performed.

Effect size

For the statistical tests in type 1, 2, and 3, unstandardised effect sizes will be reported that result from the final models, i.e., beta-coefficients and non-linear dependency curves. For type 1, pseudo-R^2 measures will be calculated based on residual variance. For type 4, the correlation coefficients are effect sizes.

Significance levels

For statistical tests in type 1, 2, and 4, p-values are calculated and corrected for multiple testing. Values equal to or below 0.05 are considered significant. For type 1 and 2, p-values are calculated through a likelihood ratio test of models with and without a parameter in question. For type 3, model selection/significance is based on Akaike's

Information Criterion (AIC), where the more complex model is to be preferred if their AIC is two or more below the less complex model. For type 4, p-values are calculated through the asymptotic t-approximation (Press et al., 1992). For type 5, 95% confidence intervals are calculated based on 10^5 bootstrapping samples. If the value of interest, i.e., a standard deviation of 0, is not within the confidence interval, it will be considered significantly different.

Data exclusion

Exclusion criteria of data

Measurement data are excluded, if their values lie outside plausible thresholds of the measurement equipment (≥130.000 lx for illuminance)

Outlier handling

Not outlier handling is expected to be necessary.

Awareness checks

No awareness checks were implemented.

Missing data

Definition of missing data

The missing data percentages (implicit missing data) and percentage data where the recorded photopic illuminance falls outside SPECCY's effective measuring range of 1 lx – 130,000 lx (explicit missing data) will be recorded and analysed.

How do deal with missing data

All implicit missing data will be made explicit in the analysis, i.e., gaps in the time-series will be filled and measurement values set to NA. Participant days with more than a threshold percentage of missing data will be excluded from further analysis. The threshold will be determined by a sensitivity analysis using three randomly chosen light exposure metrics and three randomly selected participants without missing data. The threshold will be set so that the average of each metric stays within a 95% confidence interval based on their original variation (mean±2 SE) and 10^4 resamples for each threshold. This ensures a threshold that does not significantly affect metric calculation, based on the actual data.

References

Ansu Baidoo, V., & Knutson, K. L. (2023). Associations between circadian disruption and cardiometabolic disease risk: A review. *Obesity (Silver Spring, Md.)*, *31*(3), 615–624. https://doi.org/10.1002/oby.23666

Barroso, A., Simons, K., & De Jager, P. (2014). Metrics of circadian lighting for clinical investigations. *Lighting Research & Technology*, *46*(6), 637–649. https://doi.org/10.1177/1477153513502664

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Bivand, R., & Luque, S. (2023). *suntools: Calculate Sun Position, Sunrise, Sunset, Solar Noon and Twilight*. 1.0.0. https://doi.org/10.32614/CRAN.package.suntools

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh sleep quality index: A new instrument for psychiatric practice and research. *Psychiatry Research*, *28*(2), 193–213. https://doi.org/10.1016/0165-1781(89)90047-4

Christensen, R. H. B. (2010). *ordinal: Regression Models for Ordinal Data*. 2023.12-4.1. https://doi.org/10.32614/CRAN.package.ordinal

Fernández-Martínez, M., Vicca, S., Janssens, I. A., Carnicer, J., Martín-Vide, J., & Peñuelas, J. (2018). The consecutive disparity index, *D*: A measure of temporal variability in ecological studies. *Ecosphere*, *9*(12), e02527. https://doi.org/10.1002/ecs2.2527

Fishbein, A. B., Knutson, K. L., & Zee, P. C. (2021). Circadian disruption and human health. *The Journal of Clinical Investigation*, *131*(19), e148286. https://doi.org/10.1172/JCI148286

Foster, R. G., Hughes, S., & Peirson, S. N. (2020). Circadian Photoentrainment in Mice and Humans. *Biology*, *9*(7), 180. https://doi.org/10.3390/biology9070180

Harrell, F. E. J. (2003). *Hmisc: Harrell Miscellaneous*. 5.1-3. https://doi.org/10.32614/CRAN.package.Hmisc

Hébert, M., Martin, S. K., Lee, C., & Eastman, C. I. (2002). The effects of prior light history on the suppression of melatonin by light in humans. *Journal of Pineal Research*, *33*(4), 198–203. https://doi.org/10.1034/j.1600-079x.2002.01885.x

Mohamed, A., Kalavally, V., Cain, S. W., Phillips, A. J. K., McGlashan, E. M., & Tan, C. P. (2021). Wearable light spectral sensor optimized for measuring daily α-opic light exposure. *Optics Express*, *29*(17), 27612–27627. https://doi.org/10.1364/OE.431373

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. (1992). *Numerical Recipes in C: The Art of Scientific Computing* (2nd ed.). Cambridge University Press.

R Core Team. (2021). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Robinson, D., & Silge, J. (2022). *widyr: Widen, Process, then Re-Tidy Data*. https://CRAN.R-project.org/package=widyr

Roenneberg, T., & Merrow, M. (2016). The Circadian Clock and Human Health. *Current Biology*, *26*(10), R432–R443. https://doi.org/10.1016/j.cub.2016.04.011

Siraji, M. A., Lazar, R. R., van Duijnhoven, J., Schlangen, L. J. M., Haque, S., Kalavally, V., Vetter, C., Glickman, G. L., Smolders, K. C. H. J., & Spitschan, M. (2023). An inventory of human light exposure behaviour. *Scientific Reports*, *13*(1), 22151. https://doi.org/10.1038/s41598-023-48241-y

Wickham, H. (2016). *tidyverse: Easily Install and Load the 'Tidyverse'*. 2.0.0. https://doi.org/10.32614/CRAN.package.tidyverse

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., … Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wood, S. (2000). *mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation*. 1.9-1. https://doi.org/10.32614/CRAN.package.mgcv

Zauner, J., Hartmeyer, S., & Spitschan, M. (2024). *LightLogR: Reproducible analysis of personal light exposure data with an open-source R package*. https://doi.org/10.31219/osf.io/qk924