Journal of Environmental Psychology 115 (2026) 103192

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.sciencedirect.com/journal/journal-of-environmental-psychology

Impact of light on well-being and mood in everyday life: A longitudinal study on timing, quantity, duration, and frequency of exposure

Fernanda S. Bonatto [a,b], Ricardo R.B. Correia [c], Rogério B. Borges [d,e], Luísa K. Pilz [f,g], Pedro O. Macedo [a,b], Kiara Skalnes [a,b], Marco Idiart [c], Fernanda G. Amaral [h], Maria Paz Hidalgo [a,b,*]

[a] Laboratório de Cronobiologia e Sono, Hospital de Clínicas de Porto Alegre, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil
[b] Graduate Program in Psychiatry and Behavioral Sciences, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil
[c] Institute of Physics, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil
[d] Unidade de Bioestatística – Diretoria de Pesquisa (DIPE), Hospital de Clínicas de Porto Alegre, Porto Alegre, Rio Grande do Sul, Brazil
[e] Department of Statistics, Institute of Mathematics and Statistics, Universidade Federal do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil
[f] Charité – Universitätsmedizin Berlin, corporate member of Freie Universität Berlin and Humboldt-Universität zu Berlin, ECRC Experimental and Clinical Research Center, Berlin, Germany
[g] Charité – Universitätsmedizin Berlin, corporate member of Freie Universität Berlin and Humboldt-Universität zu Berlin, Department of Anesthesiology and Intensive Care Medicine CCM | CVK, Berlin, Germany
[h] Department of Physiology, Universidade Federal de São Paulo, São Paulo, Brazil

ARTICLE INFO

Keywords:
Melanopic
Light exposure
Circadian rhythm
Sleep
Mental health

ABSTRACT

Light exposure impacts mood and well-being. Although the light–dark cycle is the primary external cue for circadian entrainment, built environments often attenuate natural day–night light variation through architectural, urban, and behavioural factors. Consequently, understanding how light exposure patterns relate to mental health requires longitudinal studies under everyday conditions. In this study, we establish and apply methods to measure and evaluate the effects of melanopic equivalent daylight illuminance (melanopic EDI) on mood and well-being. Melanopic EDI was estimated using wrist-worn sensors, alongside daily mood and well-being assessments for up to 44 days in 172 participants. Associations were examined at both within-subject and between-subject levels. Among the main findings, daytime melanopic EDI exposure, particularly in the first hours after waking, showed consistent benefits: for example, ≥15 min at ≥250 lx in the first hour after waking was associated with higher well-being scores (β_W= 0.175, $SE = 0.030$, $p < 0.001$). In contrast, ≥15 min of >1 lx during nighttime sleep was associated with poorer mood and well-being outcomes (e.g., well-being: $\beta_W = -0.107$, $SE = 0.034$, $p = 0.002$). Unexpectedly, greater exposure to melanopic EDI >10 lx within the 3 h before sleep was associated with higher daytime concentration, energy, and well-being. Association patterns varied across different mood-related outcomes, reflecting the complexity of mood construct. These findings advance understanding of how the quantity, timing, duration, and frequency of melanopic EDI exposure influence mood. By providing a temporal framework for these effects, this study highlights the relevance of individual differences and optimal exposure windows, contributing to the development of light-based interventions and lighting design strategies to enhance mental health.

1. Introduction

Light impacts mood both directly, by affecting brain areas involved in mood regulation (Copenhaver et al., 2022; Hattar et al., 2006; LeGates et al., 2014; Weil et al., 2022), and indirectly, through light-dark entrainment of the suprachiasmatic nucleus (SCN) – a key structure of the central circadian timing system (Ralph et al., 1990). Light cues are transmitted to the SCN through intrinsically photosensitive retinal ganglion cells (ipRGCs), which contain the photopigment melanopsin, most sensitive to short-wavelength light (Brainard et al.,

The data supporting this study's findings are available from the corresponding author (MPH) upon reasonable request.

* Corresponding author. Ramiro Barcelos, 2350, CPC–sala 21514 – Santa Cecilia, Porto Alegre, RS, 90035–903, Brazil.
E-mail address: mhidalgo@hcpa.edu.br (M.P. Hidalgo).

https://doi.org/10.1016/j.jenvp.2026.103192
Received 13 August 2025; Received in revised form 26 August 2026; Accepted 26 August 2026
Available online 28 August 2026

2001; Thapan et al., 2001).

While the natural light-dark cycle is the most powerful *zeitgeber* (from German, "time-giver") for synchronizing circadian rhythms (Aschoff, 1960), individuals in built environments, such as indoor or urban settings, are more exposed to electric light than natural daylight. Electric lighting typically has lower illuminance levels and a different spectral composition than daylight and can also increase light exposure in periods of environmental darkness. These unnatural patterns in exposure to light-dark can disrupt the body's regulation of circadian rhythms (Knoop et al., 2020; Wirz-Justice et al., 2020) and subsequently negatively affect mood and well-being (Bonatto et al., 2024).

However, the relationship between light and mood in healthy adults living under everyday conditions remains inconsistent, with studies employing heterogeneous methodologies and reporting mixed findings (Böhmer et al., 2021; Nixon et al., 2023). A limited number of everyday-life studies have combined repeated or daily assessments of

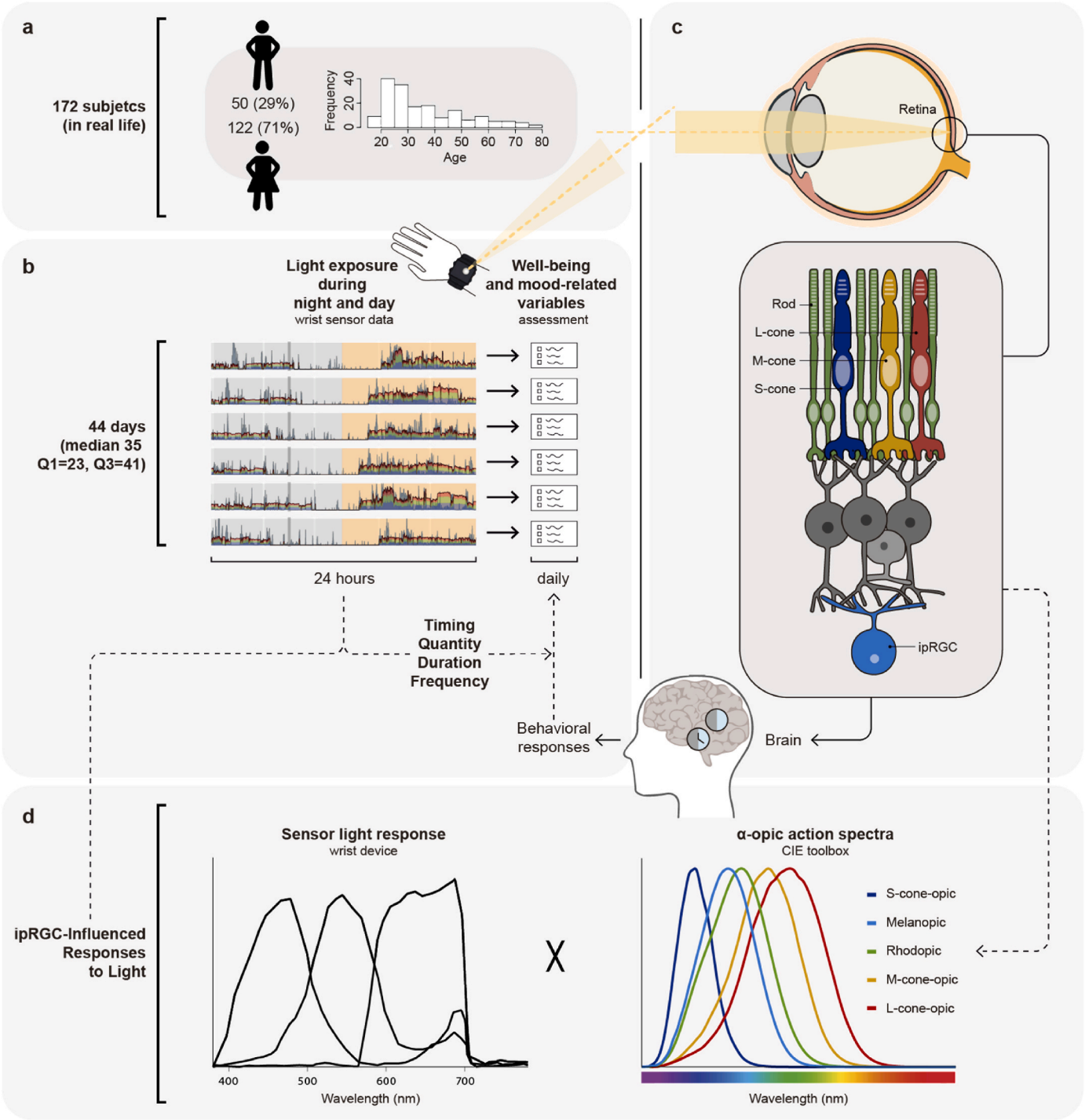


Fig. 1. Study design. a) Sample characteristics; b) Participants wore wrist devices with light sensors and answered daily questionnaires for mood-related symptoms (anxiety, sadness, appetite, sleepiness, concentration, and energy) and well-being; c) The melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs) transmit photic information to many brain structures. Evidence suggests that all receptor types, including rods and cones, can contribute to ipRGC–influenced light effects; d) To obtain the measures that characterise ipRGCs-influenced responses to light, the raw sensor data were converted to α-opic equivalent daylight illuminance using coefficients calculated from a method to combine the sensor response curves and the α-opic action spectra (CIE, 2020).

affective states with light exposure measures, reporting associations with alertness, vitality, or mood (aan het Rot et al., 2008; Hubalek et al., 2010; Smolders et al., 2013; Didikoglu et al., 2023). At the same time, properties of light exposure have been studied for their role in physiological responses to light stimuli (Bonatto et al., 2024; Brown, 2020; Cajochen, 2007; de Zeeuw et al., 2019; Rahman et al., 2017; St Hilaire et al., 2022). These properties include the combination of light spectrum, luminous flux, and their interaction with the environment, which determines illuminance levels. Other important factors include the timing, duration, and pattern of exposure.

Studying biological rhythms in everyday life conditions poses substantial methodological challenges, as it often requires repeated measurements over 24 h and across extended periods. Although wearable loggers–such as actigraphy devices that record light exposure, rest/activity, and temperature–have facilitated the measurement of biological rhythms through continuous 24-h monitoring, most of the devices provide lighting metrics based on photopic vision, which describe a condition of luminous sensation, but do not account for the broader effects of light on physiology. To estimate ipRGCs-influenced responses to light, the International Commission on Illumination (Commission Internationale de l'Eclairage-CIE) standardised consensus-based metrics that characterise light spectra according to the five photoreceptor responses (CIE, 2018). The α-opic quantities represent the spectral sensitivity of each photoreceptor type (S-cone-opic, M-cone-opic, L-cone-opic, rhodopic, and melanopic). The α-opic equivalent daylight illuminance (EDI) is defined as the illuminance level of standard daylight (D65) that produces the same α-opic irradiance as the test light (CIE, 2018). Recently, melanopic equivalent daylight illuminance (melanopic EDI) has been recommended as a metric for estimating ipRGC stimulation (Brown et al., 2022; CIE, 2024). However, further research is needed to explore the impact of melanopic EDI in everyday life settings and better understand how the timing, duration, and pattern of exposure interact, affecting well-being and mood-related outcomes. Bridging this knowledge gap requires the development of robust methodologies that can be reproduced across different populations and cultures.

This study contributes to this effort through the development of a method in which wrist-worn actigraphy light data are used to estimate melanopic EDI levels and their association with mood-related items and well-being, analysed both between and within subjects (Fig. 1). Specifically, we examined in a longitudinal everyday life study (i) the time intervals in which light exposure affects mood-related symptoms and well-being, (ii) how different illuminance levels influence these outcomes, and (iii) the duration and frequency of exposure associated with improvements in mood-related symptoms and well-being.

2. Methods

2.1. Participants

The study was approved by the Brazilian National Committee of Ethics in Research (Comissão Nacional de Ética em Pesquisa – CONEP; CAAE 30396320.1.0000.5327) and conducted according to the Declaration of Helsinki.

We carried out the study between April 2020 and January 2021 in the Brazilian states of Rio Grande do Sul (RS) and São Paulo (SP). Throughout the study, the difference between the longest and shortest photoperiods in RS was 3.81 h, with a mean day length of 11 h and 1 min (sunrise [h:mm; mean ± SD] = 6:52 ± 0:09; sunset = 17:53 ± 0:07), while in SP this difference was 2.92 h, with a mean day length of 11 h and 7 min (sunrise [h:mm; mean ± SD] = 6:34 ± 0:06; sunset = 17:41 ± 0:05) (Supplementary Figure S1).

Recruitment targeted volunteer adults who were adhering to social distancing measures during the COVID-19 pandemic (e.g., remote work or study following the closure of schools, universities, and non-essential businesses). Inclusion criteria were being 18 years of age or older, ability to understand Portuguese, and ability to complete daily questionnaires. Exclusion criteria were medical conditions associated with mobility limitation that could bias actigraphy recordings, the presence of decompensated chronic illness, and current suicide risk or indication for psychiatric hospitalization.

A total of 172 participants (RS = 97; SP = 75) were included in the study (sample characteristics in Table 1) and collected data for up to 44 days (median [lower–upper quartile] = 35 [23–41]). The age range of the participants was 18–77 years (mean ± SD = 36 ± 15); 70.9% were female; 77.9% of the participants were in social distancing (more than half or all the time); and only 27.3% were not allowed to choose their work schedules.

2.2. Measures

2.2.1. Light exposure

Light exposure was measured using wrist-worn actigraphy devices (ActTrust, Condor Instruments Ltd.), which incorporate a triaxial accelerometer, temperature sensor, and multichannel optical sensors. The light-sensing module is composed of independent photodiodes with spectral responsivity in the blue (λ_{peak} = 470 nm), green (λ_{peak} = 538 nm), and red (λ_{peak} = 630 nm) regions of the spectrum. The system operates over a broad dynamic range (0.01–8388.61 μW/cm^2) with typical precision of approximately 10% at 10 μW/cm^2. Light exposure was recorded in 1-min epochs.

2.2.2. Questionnaires

2.2.2.1. Mood-related symptoms. Levels of affective (anxiety and sadness), somatic (sleepiness and appetite), and cognitive (concentration and energy) symptoms were assessed using the original Brazilian Portuguese version of the *Mood Rhythm Reduced Diary* (MRh–RD), rated on a scale of 0–10 (Nexha et al., 2024). The items were related to mood disorders and were chosen based on the factor analysis of the validated *Mood Rhythm Instrument* (Alves Braga de Oliveira et al., 2021), an instrument originally developed to assess whether symptoms related to mood disorders follow a daily pattern with an identifiable peak at a specific time of the day. At the end of each day, participants retrospectively rated the MRh–RD items for five time points: 0, 3, 6, 9, and 12 h after awakening. Because variation across time-point-level reports was minimal (Nexha et al., 2024), we calculated the daily average of those variables for the analysis. Table 2 presents the sample mean and standard deviation.

2.2.2.2. Well–being. Psychological daily well-being was assessed using the Brazilian Portuguese-validated version of the self-reported questionnaire *Five-item World Health Organization Well-Being Index* (WHO-5),

Table 1
Sample characteristics (n = 172).

Sex: female, *n* (%)	122 (70,9)
Age: years, mean ± SD	36 ± 15
Schooling: *n* (%)	
PhD	13 (7.6)
Master's degree	25 (14.5)
Bachelor's degree	81 (47.1)
High school	52 (30.2)
Middle school	1 (0.6)
Social distancing adherence: *n* (%)	
All the time	62 (36.0)
More than half of the time	72 (41.9)
Less than half of the time	5 (2.9)
No social distancing	1 (0.6)
No data	32 (18.6)
Work/study flexibility: *n* (%)	
Allowed to choose schedules	97 (56.4)
Not allowed to choose schedules	47 (27.3)
Not working/studying	28 (16.3)

Table 2
Descriptive statistics of light exposure, sleep timing, and mood-related outcomes in the study sample (n = 172).

Variable	Statistic	Value
Light exposure		
Nighttime melanopic EDI, lx	median [Q1–Q3]	0.06 [0.04–7.15]
Melanopic EDI within 3 h before sleep onset, lx	median [Q1–Q3]	4.13 [0.27–15.0]
Melanopic EDI at night during the sleep period, lx	median [Q1–Q3]	5.44 [0.53–17.15]
Daytime melanopic EDI, lx	median [Q1–Q3]	57 [14–215]
Melanopic EDI within 1 h after wake-up, lx	median [Q1–Q3]	9.8 [0.2–63.2]
Melanopic EDI within 2 h after wake-up, lx	median [Q1–Q3]	27.0 [1.8–120.4]
Melanopic EDI within 3 h after wake-up, lx	median [Q1–Q3]	40.1 [5.5–161.5]
Daily maximum melanopic EDI, lx	median [Q1–Q3]	9734 [1811–33,684]
Timing of daily maximum melanopic EDI, h:mm	mean ± SD	12:59 ± 2:25
Last melanopic EDI >10 lx before sleep onset, h:mm	median [Q1–Q3]	23:20 [22:30–23:55]
Time from last melanopic EDI >10 lx to sleep onset, h:mm	median [Q1–Q3]	1:18 [0:30–2:30]
First daytime melanopic EDI ≥250 lx, h:mm	mean ± SD	10:00 ± 1:56
Time from wake-up to first daytime melanopic EDI ≥250 lx, h:mm	median [Q1–Q3]	1:06 [0:30–2:05]
Duration of melanopic EDI >10 lx within 3 h before sleep onset, min/night	mean ± SD	43.8 ± 45.6
Duration of melanopic EDI >1 lx during the sleep period, min/night	mean ± SD	6.6 ± 19.8
Duration of daytime melanopic EDI ≥250 lx, h:mm/day	mean ± SD	1:53 ± 1:52
Sleep variables		
Wake-up time, h:mm	mean ± SD	8:32 ± 0:30
Sleep onset time, h:mm	mean ± SD	0:45 ± 0:30
Midpoint of sleep, h:mm	mean ± SD	4:41 ± 1:41
Outcomes		
Anxiety, level	mean ± SD	2.5 ± 2.4
Sadness, level	mean ± SD	1.7 ± 2.2
Appetite, level	mean ± SD	3.9 ± 1.5
Sleepiness, level	mean ± SD	2.9 ± 2.0
Concentration, level	mean ± SD	5.0 ± 2.1
Energy, level	mean ± SD	5.1 ± 1.9
Well-being, score	mean ± SD	13.5 ± 5.6

Melanopic EDI: melanopic equivalent daylight illuminance.
Anxiety, sadness, appetite, sleepiness, concentration, and energy were assessed using the Mood Rhythm Reduced Diary (MRh–RD) on a scale from 0 to 10; Well-being was evaluated using the Five-item World Health Organization Well-Being Index (WHO-5), with a total score on a scale from 0 to 25.

rated on a 0-25 score (de Souza & Hidalgo, 2012). This scale is well-established in the literature, with a recommended score of ≤ 50% (13 points) for clinical depression screening (Topp et al., 2015). Validation of the WHO-5 in a Brazilian sample indicated that scores below 20 suggested depressive disorders (de Souza & Hidalgo, 2012). Supplementary Figure S5 shows the relationship between the average MRh-RD daily symptoms and daily WHO-5 scores.

2.2.2.3. Sleep. Participants reported their sleep onset and wake times daily. For each day, we calculated the midpoint of sleep (sleep phase). Naps were not considered.

2.3. Procedures

Participants were recruited through online platforms and a snowball sampling strategy. All participants received information about the study via telephone, email, and text before the initial battery of questionnaires. They agreed to participate during the phone call and provided informed consent by checking a checkbox in the initial survey. Participants wore wrist devices with light sensors and answered retrospective daily online questionnaires for mood-related symptoms, well-being, and sleep timing.

The actigraphy devices were delivered to participants' homes in accordance with social distancing measures. Actigraphy instructions were sent via text and video and included: guidance to wear the device continuously (including during sleep); placement on the non-dominant wrist, directly on the skin and uncovered; information that the device was water-resistant but not suitable for swimming; and advice to limit any removal to no more than 40 minutes. They were reminded to answer their daily online questionnaires by email or text message.

2.4. Data preparation

2.4.1. Data quality control and exclusions

Data quality control procedures were applied to both the questionnaire and the light exposure data.

The questionnaire dataset comprised 178 participants and 6372 diary days. Most questionnaire entries were completed within 24 h after wake-up; 22% (1413 days) were submitted more than 24 h later, and 3% (203 days) were submitted more than 48 h after wake-up. The dataset was inspected for inconsistencies between participant-entered dates and survey submission timestamps, resulting in 18 date corrections. Duplicate entries were also reviewed, and when clear errors were identified, the second entry was retained (83 corrections), while 37 entries were excluded. This procedure resulted in 6331 valid diary days from 178 participants.

Sleep–wake reports were additionally screened to ensure temporal plausibility. Entries with sleep durations (sleep end minus sleep onset) shorter than 3 h or longer than 13 h were manually reviewed against actograms. Sleep and wake-up times were corrected when errors related to the 24-h format were clearly identifiable (e.g., reporting 11:00 instead of 23:00); otherwise, values were set to missing (NA). In total, 54 sleep onset times and 15 wake-up times were corrected, while 11 sleep onset times and 10 wake-up times were set to NA.

The actigraphy dataset comprised 172 participants and 7197 recorded days. To ensure temporal consistency, the onset of each time series was standardised to 00:00. No Daylight Saving Time changes occurred during the study period. Missing actigraphy data–defined as periods during which the device was likely off-wrist–were detected using the algorithm proposed by Pilz et al. (2022) and subsequently confirmed by visual inspection.

A total of 5971 days from 172 participants contained both valid questionnaire and light exposure data and were considered for further analyses. Exclusion criteria included days with more than 2 h of missing light data (217 out of 5971 days) and days in which sleep onset occurred after sunrise (25 out of 5754 days). After all exclusions, 5729 valid days remained for analysis. Supplementary Table S1 summarizes the data exclusion steps and final sample sizes.

2.4.2. Definition and computation of light exposure variables

Following data quality control, light exposure variables were derived for analysis. The raw sensor data were converted to α-opic EDI (lx) using coefficients calculated from a method to combine the sensor response curves with the CIE S 026:2018 α-opic Toolbox (CIE, 2020). Details on the calculation procedures are provided in the Supplementary Methods.

The duration of melanopic EDI exposure was quantified based on consensus recommendations for non-visual light exposure aimed at enhancing physiological and cognitive functions: a minimum melanopic EDI of 250 lx during the daytime, a maximum of 10 lx in the evening (starting 3 h before bedtime), and a maximum of 1 lx for the sleep environment during nighttime (Brown et al., 2022; CIE, 2024). For the evening interval, we considered 3 h before sleep onset rather than before bedtime. We computed the duration in minutes for which melanopic EDI met the daytime recommendation (≥250 lx) within 1, 2, and 3 h after

wake-up, exceeded the evening recommendation (>10 lx) within the 3 h before sleep onset, and exceeded the nighttime sleep recommendation (>1 lx) during the sleep period.

Daytime and nighttime exposure intervals were defined by local sunrise and sunset times. The photoperiod was determined for each specific date, using the coordinates of Porto Alegre (latitude: 30.04° S, longitude: 51.21° W) and São Paulo (latitude: 23.56° S, longitude: 46.64° W)–the capitals of the states of Rio Grande do Sul and São Paulo, respectively, and the cities with the highest number of entries. Sleep periods were defined daily as the interval between self-reported sleep onset and sleep end for each individual. To ensure that only nighttime minutes were included in the intervals "3 h pre-asleep" and "sleep period," we restricted these intervals to minutes occurring between sunset and sunrise. Likewise, to include only daytime minutes in the "after wake-up" intervals, we considered only minutes occurring between sunrise and sunset.

Minimum thresholds of melanopic EDI exposure duration were then defined using 30-min increments, ranging from ≥30 to ≥120 min within the 3-h intervals before sleep onset and after wake-up time, and from ≥30 to ≥90 min within the 2-h interval after wake-up. Minimal durations of ≥15 and ≥ 30 min were computed for the sleep period and the interval within 1 h after wake-up. Additionally, we computed in those intervals the absence of minutes achieving the daytime recommendations and diverging from the evening and the sleep period recommendations (identified as 0 min).

Finally, to account for the relative balance between daytime and nighttime light exposure duration, we calculated the exposure duration ratio by subtracting the total of minutes exceeding the recommendation during the night intervals ("3 h pre-asleep" and "sleep period") from the total time achieving the recommendation during the day and then dividing this difference by the sum of these two durations. We named this variable the "relative duration of light exposure" (RDLE). RDLE is therefore given by:

$$RDLE = \frac{x_{day} - y_{night}}{x_{day} + y_{night}},$$

where x_{day} is:

$$\sum_{sunrise}^{sunset} I(mEDI_i \geq 250),$$

and y_{night} is:

$$\sum_{sleep\ onset-3h}^{sleep\ onset} I(mEDI_i > 10)\, I(night_i) \quad or \quad \sum_{sunset}^{sunrise} I(mEDI_i > 1)\, I(sleep_i),$$

where $mEDI_i$ and $sleep_i$ are the melanopic EDI exposure level and current state (awake or asleep) at the ith minute of the corresponding period, respectively.

2.5. Statistical analysis

We examined whether light exposure was associated with the outcomes of anxiety, sadness, sleepiness, appetite, concentration, energy, and well-being using robust linear mixed–effects regression models (Rlmer). Daytime light exposure was tested as a predictor of same-day outcomes, while nighttime light exposure was assessed as a predictor of next-day outcomes. The Rlmer models were designed to assess both between-subject effects (individual mean across all days of recording) and within-subject effects (variation around each individual's mean) (van de Pol & Wright, 2009). The between-subject effect reflects differences between individuals, indicating whether participants with higher light exposure (quantity or duration) across the study period tend to have different outcome levels compared to those with lower exposure. In contrast, the within-subject effect reflects day-to-day variation within individuals, indicating whether deviations from an individual's mean of light exposure are associated with changes in their own outcomes. The models included random intercepts for participants, with days nested within participants. Statistical results were presented with a significance threshold of $p \leq 0.05$.

The quantity of melanopic EDI exposure within each interval was estimated using the median, which best reflects the data distribution, given the presence of outliers at certain times (Supplementary Figure S2), and analysed using its natural logarithm transformation. We conducted two analyses: (i) In the first analysis, light exposure intervals were based on clock time, dividing the 24-h day into 1-h segments, with each interval spanning 60 min (e.g., 00:00 to 00:59). Separate models were fitted for each hourly light exposure interval. The Rlmer models were adjusted for sex, age, and wake–up time; (ii) in the second analysis, the light exposure intervals were defined in 30-min increments relative to each participant's sleep time–preceding sleep onset and following wake-up time–resulting in cumulative intervals that included the previous one (e.g., 30 min, 1 h, 1.5 h). We excluded minutes before sleep onset if they were before sunset, and minutes after wake-up if they were before sunrise. Separate models were also fitted for each interval. The Rlmer models were adjusted for sex, age, and the midpoint of sleep. Both analyses of the quantity of light were also performed for other α-opic EDI and photopic illuminance as predictor variables, as shown in Supplementary Figures S6 to S9.

The duration of melanopic EDI exposure was analysed in intervals within the 3 h pre-sleep, within the sleep period, and within 1 h, 2 h, and 3 h after wake-up. We performed the Rlmer models to analyse the melanopic EDI exposure duration thresholds assessed over a 7-day frequency with the 7-day average of mood-related symptoms and well-being scores. The 7-day periods were computed using a rolling window approach across the dataset. Analyses were adjusted for sex, age, and midpoint of sleep. Models for duration and frequency in intervals of 3 h before sleep onset and within the sleep period were further adjusted for the RDLE to account for the relative balance between daytime and nighttime light exposure duration (Supplementary Figure S4). A post-hoc power analysis was conducted assuming a detectable effect size of a 2.5-point increase in WHO-5 scores in relation to melanopic EDI exposure duration over 7 days, with all effects tested at the 5% significance level (Green & MacLeod, 2016). Across all models, the calculated power exceeded 95%.

Given the delayed questionnaire completion described in the data quality control section (Section 2.4.1), separate sensitivity analyses were performed for all models excluding entries submitted more than 48 h after awakening (180 days, 3.14% of the 5729 valid days). The results, provided in the Supplementary Sensitivity Analyses, were similar to those of the main models, with preserved coefficient directions and only minor changes in statistical significance.

Statistical analyses were performed using R software (v. 4.4.0, RStudio 2024.04.1 + 748; R–packages: simr (Green & MacLeod, 2016) for power analysis; ggplot2 (Wickham, 2016) for data visualisation; solartime (Wutzler, 2021) for estimating the photoperiods of São Paulo and Porto Alegre; robustlmm (Koller, 2016) to fit Rlmer models; emmeans (Lenth et al., 2025) and ggeffects (Lüdecke, 2018) to post hoc test. Supplementary Methods provide detailed statistical procedures.

3. Results

Table 2 summarizes light exposure characteristics, sleep timing, and outcome variables in the study sample. Fig. 2 shows the sample's double-plotted daily melanopic EDI profile, illustrating the temporal distribution of exposure across the 24-h cycle in relation to sunrise, sunset, sleep onset, and wake-up time. However, both the levels and temporal patterns of light exposure varied substantially across participants. Individual double-plotted daily melanopic EDI profiles are provided in the Supplementary Information (Figures S3a–S3d).

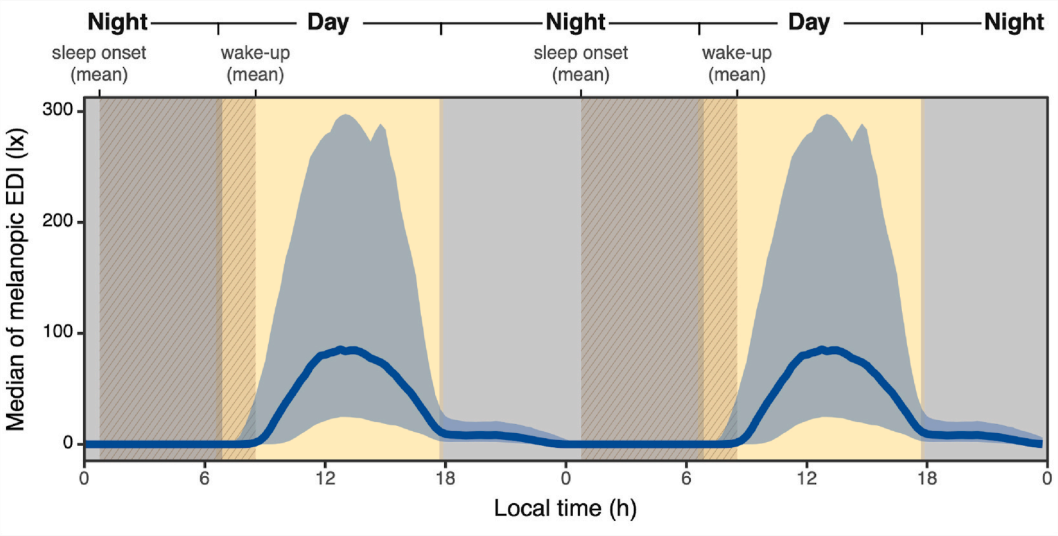


Fig. 2. Double-plotted daily melanopic EDI profile of the sample. The blue line represents the median melanopic EDI exposure across days, and the blue ribbon represents the interquartile range. Grey-shaded rectangles represent the period between sunset and sunrise (night), while yellow-shaded rectangles represent the period between sunrise and sunset (day). The brown hatched areas, which comprise part of the night and day periods, represent the interval between the sample mean sleep onset time (00:45) and wake-up time (08:32). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1. Quantity and timing

To address the objectives related to (i) the time intervals during which light exposure affects mood-related symptoms and well-being and (ii) how different levels of melanopic EDI influence these outcomes, we analysed between-subject and within-subject associations between melanopic EDI exposure across the 24-h day and daily mood-related symptoms and well-being scores.

Fig. 3 shows the coefficients from Rlmer models, demonstrating the effects of melanopic EDI exposure within each 1-h interval (Supplementary Tables S2 and S3). The results indicated fewer between-subject than within-subject associations between melanopic EDI exposure and mood, although the coefficients for within-subject associations were smaller.

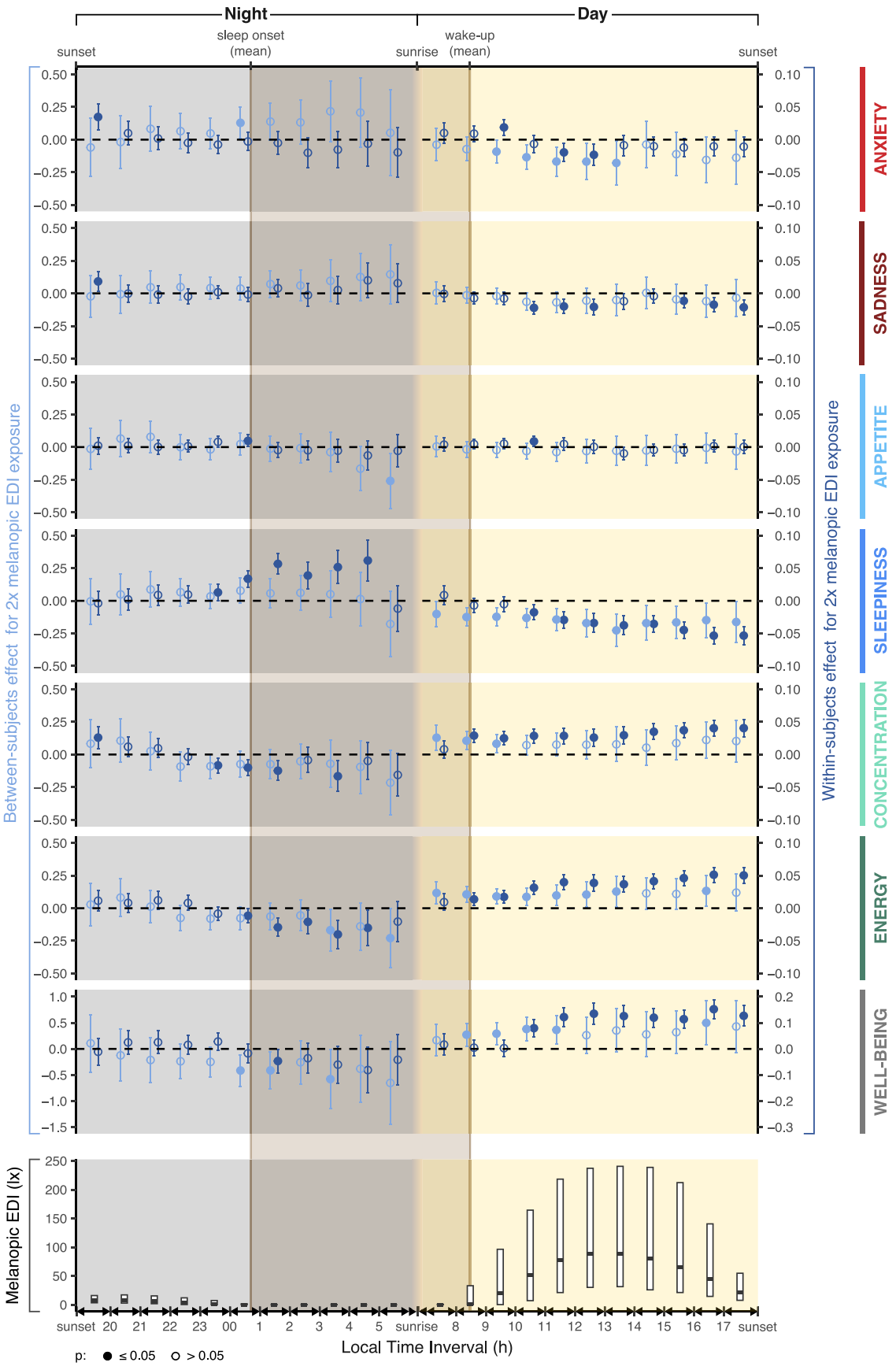
At the between-subject level, the earliest daytime associations of median melanopic EDI exposure were observed in the sunrise–7:59 interval, with lower sleepiness ($\beta_B = -0.044$, 95% CI [–0.085, −0.003]) and higher concentration ($\beta_B = 0.056$, 95% CI [0.015, 0.097]) and energy levels ($\beta_B = 0.051$, 95% CI [0.014, 0.087]). One hour later, significant associations emerged for well-being scores ($\beta_B = 0.118$, 95% CI [0.023, 0.213]), while effects on anxiety ($\beta_B = -0.040$, 95% CI [−0.078, −0.002]) became evident about 2 h after the initial interval. Notably, the association with reduced sleepiness was found across all analysed daytime intervals, and no associations were observed for sadness and appetite. During nighttime intervals, isolated associations were observed with next-day higher anxiety and lower appetite, and some associations with next-day lower energy levels and well-being scores. No associations were observed for sleepiness or concentration.

Regarding within-subject results, Fig. 3 shows that the earliest daytime associations of median melanopic EDI exposure were observed in the 8:00–8:59 interval, with higher levels of concentration ($\beta_W = 0.013$, 95% CI [0.008, 0.017]) and energy ($\beta_W = 0.006$, 95% CI [0.002, 0.010]). Two hours later, significant associations emerged for reduced sadness ($\beta_W = -0.010$, 95% CI [−0.014, −0.005]) and sleepiness ($\beta_W = -0.008$, 95% CI [−0.013, −0.003]), and increased well-being scores ($\beta_W = 0.035$, 95% CI [0.020, 0.049]). At the end of the morning, there were associations with lower levels of anxiety (11:00–11:59, $\beta_W = -0.008$, 95% CI [−0.015, −0.002]). On the other hand, during the night, the earliest association was observed within the 23:00–23:59 interval with higher levels of sleepiness ($\beta_W = 0.006$, 95% CI [0.000, 0.011]) and lower levels of concentration ($\beta_W = -0.007$, 95% CI [−0.012, −0.002]) the following day. One hour later, significant associations emerged for next-day reduced energy ($\beta_W = -0.005$, 95% CI [−0.010, 0.000]). For anxiety, sadness, and well-being, only one within-subject association was identified during the night. For appetite, a single within-subject association was observed during the day, and another during the night.

Fig. 4 presents between-subject and within-subject associations of median melanopic EDI exposure related to the sleep period with daily mood-related symptoms and well-being scores, based on cumulative intervals in 30-min increments preceding sleep onset and following wake-up time (Supplementary Tables S4 and S5). Building upon the findings from the previous analysis, the Rlmer models revealed the predominance of within-subject associations over between-subject associations.

Between subjects, median melanopic EDI exposure after wake-up was associated with lower anxiety in one interval and with lower sleepiness and higher concentration and energy in a limited number of intervals. No between-subject associations were observed in intervals preceding sleep onset, except for a single interval associated with increased sleepiness the following day. For sadness, appetite, and well-being, no between-subject associations were observed in any interval, either before or after the sleep period (Fig. 4).

Regarding within-subject effects, higher median melanopic EDI exposure after wake-up was associated with lower levels of sadness and sleepiness, higher levels of concentration and energy, and higher well-being scores. Specifically, associations with concentration and energy were found across all ‘after-wake-up time’ intervals. Before sleep onset, a few associations were observed. Contrary to expectations, increased median melanopic EDI exposure before sleep onset was associated with higher next-day concentration and energy levels and higher next-day well-being scores. Melanopic EDI exposure during the night period showed no within-subject associations with anxiety, sadness, appetite, sleepiness, and concentration. Overall, Fig. 4 also shows a tendency for increasing post-awakening association coefficients as the median interval melanopic EDI exposure and the extension of cumulative intervals increase. The highest effect was observed in the longest interval, corresponding to the entire awake daytime period (from wake-up time to



(caption on next page)

Fig. 3. Between-subject and within-subject coefficients from separate robust linear mixed–effects regression models for each hourly interval and outcome. Daily mood-related symptoms (MRh–RD: Mood Rhythm Reduced Diary) and well-being scores (WHO-5: Five-item World Health Organization Well-Being Index) were regressed on median melanopic EDI exposure over the 24-h day. The "effect for 2x median melanopic EDI" refers to the estimated effect associated with a doubling of the median melanopic EDI in the corresponding time period. In the top seven plots, solid dots show coefficients of significant associations ($p \leq 0.05$) and whiskers represent their 95% confidence intervals. In the bottom plot, a simplified boxplot displays the first, second, and third quartiles of melanopic EDI exposure across subjects. Grey–shaded rectangles represent the period between sunset and sunrise (night) and indicate associations with next-day outcomes; yellow–shaded rectangles represent the period between sunrise and sunset (day) and indicate associations with same–day outcomes. The brown shaded area that comprises part of night and day in the figure represents the period between sleep onset time (00:45) and wake–up time (08:32) sample means. Analyses were adjusted for sex, age, and wake-up time. Note that the vertical axis scales differ between well-being and other outcomes, within-subject effects (rightmost values, dark blue dots), and between-subject effects (leftmost values, light blue dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sunset).

The association patterns of median melanopic EDI exposure in our models, both throughout the 24-h day and during the sleep period, were generally similar to those found when analysing the median of other α-opic EDIs, photopic illuminance, and the device light variable as predictors. Supplementary Figures S6 to S9 present these results.

3.2. Duration and frequency

To address the objective related to how the duration and frequency of light exposure are associated with mood-related symptoms and well-being, we first characterised daily exposure relative to current consensus recommendations (Brown et al., 2022; CIE, 2024). Summary characteristics of light exposure are presented in Table 2, and Supplementary Table S6 presents the percentage of days classified according to the duration for which melanopic EDI met the daytime recommendation (≥250 lx) or exceeded the evening/nighttime recommendations (>10 lx and >1 lx) across each daily time interval.

Frequency and duration refer to how often, within 7-day intervals, melanopic EDI exposure met daytime or exceeded nighttime recommendations for at least 15, 30, 60, 90, or 120 min. Overall, within-subject associations were substantially more frequently observed than between-subject associations. Fig. 5 presents the within-subject results from the Rlmer models, while Supplementary Tables S7 and S8 report the between-subject and within-subject coefficients, respectively.

Fig. 5 shows that, within subjects, a greater number of nights with melanopic EDI exposure > 10 lx during the 3 h before sleep onset was associated with higher subsequent sadness for exposures exceeding 30 min ($\beta_W = 0.023$, $SE = 0.009$, $p = 0.013$) and higher subsequent appetite for exposures exceeding 60 min ($\beta_W = 0.020$, $SE = 0.007$, $p = 0.002$). Exposure to melanopic EDI > 10 lx during this period was associated with subsequent sleepiness levels for all analysed duration thresholds. However, specifically for sleepiness, melanopic EDI exposure ≤ 10 lx demonstrated a higher coefficient and the same association direction compared to exposure at levels > 10 lx, indicating that the associations are unclear during this period. Contrary to expectations, a higher number of nights with more than 60 min of exposure to melanopic EDI > 10 lx during the 3 h before sleep onset was associated with higher subsequent concentration ($\beta_W = 0.029$, $SE = 0.08$, $p < 0.001$) and energy levels ($\beta_W = 0.025$, $SE = 0.008$, $p = 0.001$). In addition, more than 30 min of exposure to melanopic EDI > 10 lx in this interval was associated with higher subsequent well-being scores ($\beta_W = 0.092$, $SE = 0.025$, $p < 0.001$).

In contrast with those 3-h pre-asleep period results, melanopic EDI exposure during the nighttime sleep period was associated with adverse subsequent mood and well-being outcomes. The nighttime sleep period was the only interval in which exposure duration levels above the thresholds demonstrated between-subject associations. Between subjects, a higher number of nights with more than 15 min of exposure to melanopic EDI > 1 lx was associated with higher sadness levels ($\beta_B = 0.309$, $SE = 0.123$, $p = 0.012$), and with more than 30 min of exposure was associated with higher anxiety ($\beta_B = 0.601$, $SE = 0.207$, $p = 0.004$) and sadness levels ($\beta_B = 0.634$, $SE = 0.171$, $p < 0.001$) as well as decreased well-being scores ($\beta_B = -1.072$, $SE = 0.531$, $p = 0.044$).

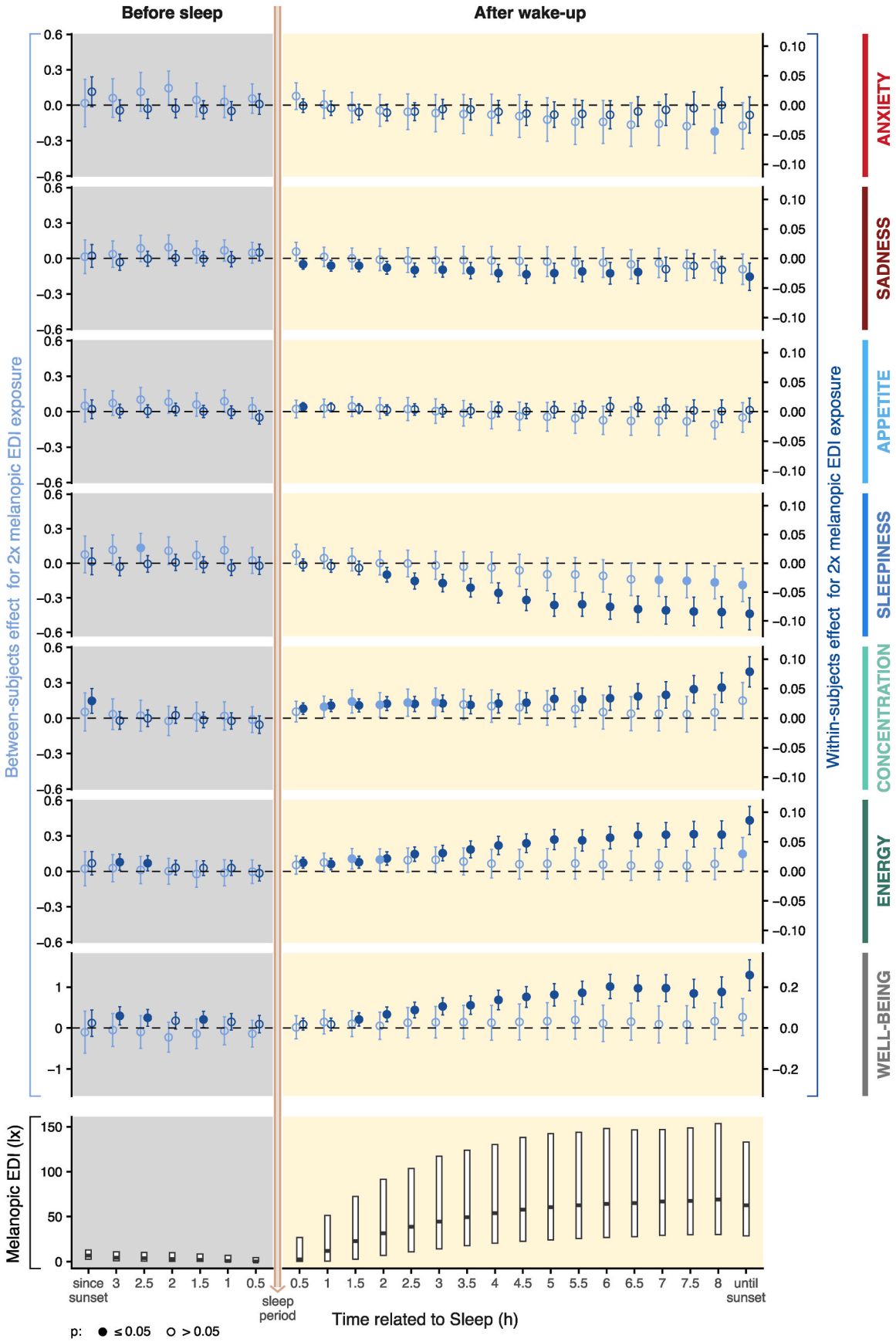
Within subjects, during the nighttime sleep period, a higher number of nights with more than 15 min of exposure to melanopic EDI > 1 lx was associated with higher subsequent anxiety ($\beta_W = 0.029$, $SE = 0.013$, $p = 0.028$), sadness ($\beta_W = 0.069$, $SE = 0.012$, $p < 0.001$), and sleepiness levels ($\beta_W = 0.023$, $SE = 0.012$, $p = 0.048$), and lower subsequent appetite ($\beta_W = -0.028$, $SE = 0.009$, $p = 0.001$), concentration ($\beta_W = -0.033$, $SE = 0.010$, $p = 0.001$) and energy levels ($\beta_W = -0.043$, $SE = 0.010$, $p < 0.001$), and well-being scores ($\beta_W = -0.107$, $SE = 0.034$, $p = 0.002$).

Regarding the periods after wake-up, within-subject results overall demonstrated that duration and frequency of melanopic EDI exposure levels ≥ 250 lx were associated with improvements in all analysed outcomes, suggesting mood-enhancing effects. Within the first hour after wake-up, more than 15 min of exposure was associated with lower anxiety ($\beta_W = -0.050$, $SE = 0.011$, $p < 0.001$), sadness ($\beta_W = -0.022$, $SE = 0.011$, $p = 0.049$), and sleepiness ($\beta_W = -0.038$, $SE = 0.010$, $p < 0.001$), and higher well-being scores ($\beta_W = 0.175$, $SE = 0.030$, $p < 0.001$), while more than 30 min of exposure was associated with increased appetite ($\beta_W = 0.025$, $SE = 0.011$, $p = 0.027$) and energy ($\beta_W = 0.059$, $SE = 0.013$, $p < 0.001$). Furthermore, the results shown in Fig. 5 indicate that the closer the melanopic EDI exposure occurred to wake-up time, the greater its impact across outcomes for a given duration threshold, except for concentration. For concentration, a significant effect was only observed when exposure exceeded 120 min within the first 3 h after waking ($\beta_W = 0.056$, $SE = 0.017$, $p = 0.01$).

4. Discussion

This study establishes methods for measuring everyday-life melanopic EDI exposure and evaluating its associations with mood-related symptoms (anxiety, sadness, appetite, sleepiness, concentration, and energy) and well-being, both between and within individuals. By integrating long-term personal light exposure data with daily assessments of mood, the study advances understanding of how light exposure characteristics – quantity, timing, duration, and frequency – relate to mental health in everyday environments. Importantly, it provides a temporal framework for melanopic EDI effects, which is essential for translating chronobiological evidence into strategies applicable to the built environment.

Given the multidimensional clinical profile of depression, including changes in sleep, appetite, energy, and concentration, it is notable that the influence of melanopic EDI exposure differed across specific symptoms. The daily mean symptom scores were associated with depressive and anxiety severity scales (Nexha et al., 2024) and with well-being, with observed associations between light and mood emerging predominantly at the within-subject level. This indicates that day-to-day fluctuations in light exposure within individuals were more strongly related to symptom variation than stable differences between individuals. This finding suggests that the relationship between light exposure and mood operates primarily through intra-individual dynamics, consistent with evidence that biological and behavioural responses to light are shaped by personal characteristics such as prior light history, daily routines, and individual sensitivity to light (Castillo et al., 2023; Chang et al., 2011; Hébert et al., 2002; Phillips et al., 2019;Refinetti, 2019;Smith et al.,



(caption on next page)

Fig. 4. Between-subject and within-subject coefficients from separate robust linear mixed–effects regression models for each interval (defined from the wake-up time and sleep onset) and outcome. Daily mood-related symptoms (MRh–RD: Mood Rhythm Reduced Diary) and well-being scores (WHO-5: Five-item World Health Organization Well-Being Index) were regressed on median melanopic EDI exposure within intervals in 30-min increments preceding sleep onset and following wake–up time (each interval included the previous one). The "effect for 2x median melanopic EDI" refers to the estimated effect associated with a doubling of the median melanopic EDI in the corresponding time period. In the top seven plots, solid dots show coefficients of significant associations ($p \leq 0.05$) and whiskers represent their 95% confidence intervals. In the bottom plot, a simplified boxplot displays the first, second, and third quartiles of melanopic EDI exposure across subjects. Grey–shaded rectangles represent the period between sunset and sleep onset (before sleep) and indicate associations with next-day outcomes; yellow–shaded rectangles represent the period between wake-up time and sunset (after wake-up) and indicate associations with same–day outcomes. Analyses were adjusted for sex, age, and midpoint of sleep. Note that the vertical axis scales differ between well-being and other outcomes, within-subject effects (rightmost values, dark blue dots), and between-subject effects (leftmost values, light blue dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2004).

The fact that light exposure affected specific mood-related symptoms differently may help explain the heterogeneous findings reported in previous studies linking light exposure to mood disorders (Böhmer et al., 2021; Burns et al., 2023; Didikoglu et al., 2023; Esaki et al., 2021). For example, while sleepiness and energy exhibited more pronounced effects of light exposure, appetite showed the least consistent association with melanopic EDI exposure, suggesting that despite its circadian regulation, its relationship with everyday light exposure remains unclear (Baron et al., 2011; Dashti et al., 2019; Lucassen et al., 2013; Maukonen et al., 2017; Muñoz et al., 2017; Scheer et al., 2013). Together, these results emphasize the importance of symptom-specific and person-centred approaches when evaluating the mental health effects of light.

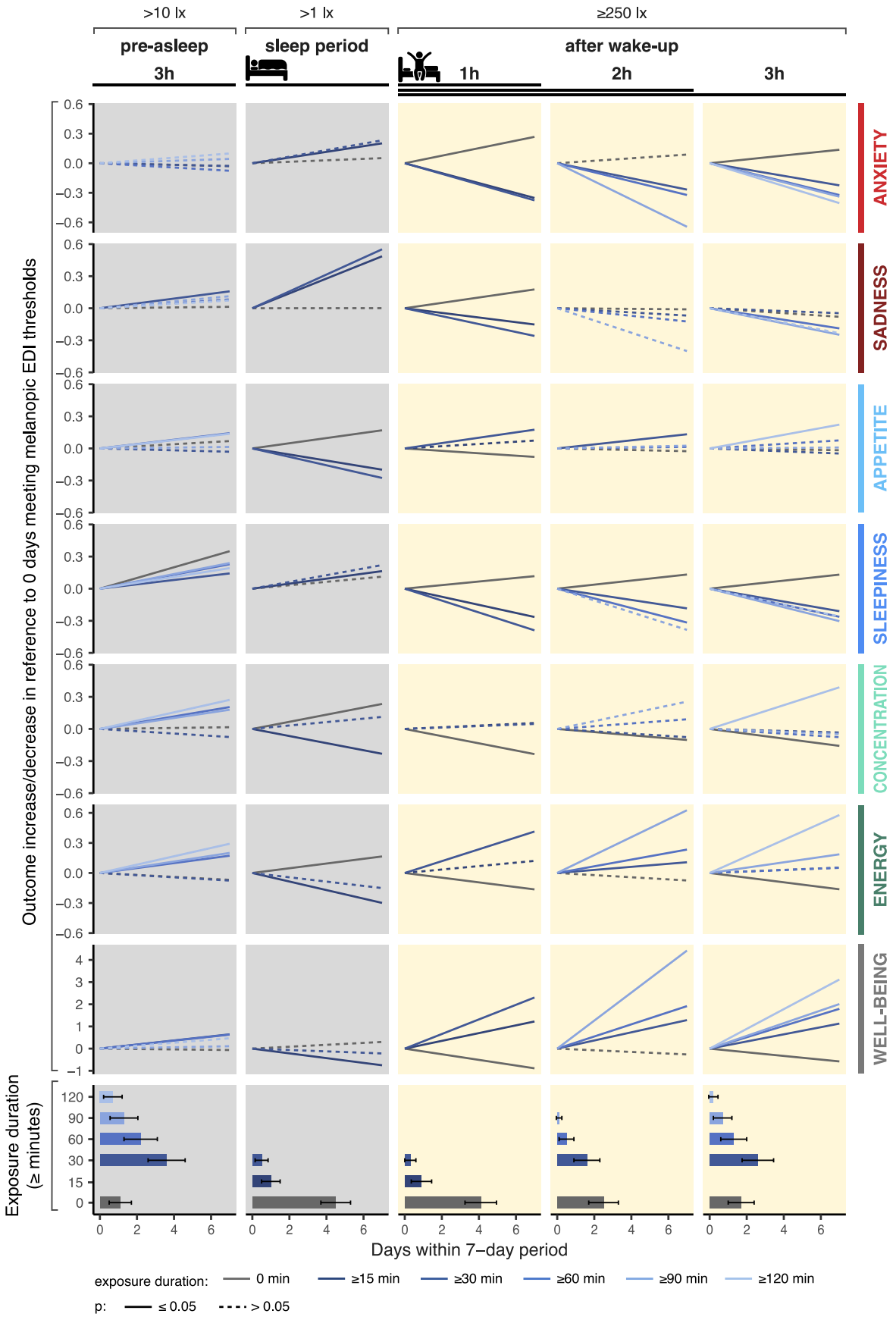
Consistent with previous literature, higher melanopic EDI exposure during nighttime was associated with adverse next-day mood and well-being outcomes. We observed that exposure to melanopic EDI $>$ 1 lx for at least 15 min during the sleep period was linked to subsequent higher anxiety and sadness, as well as reduced well-being. These findings align with evidence showing that nighttime light exposure is associated with depressive symptoms across different age groups, including in adolescents (Tonon et al., 2022), adults (Esaki et al., 2022), and the elderly (Obayashi et al., 2022). This is supported by well-established mechanisms through which nocturnal light suppresses melatonin secretion and disrupts circadian regulation (Amaral & Cipolla-Neto, 2018; Reiter, 2003; Cho et al., 2015; Tonon et al., 2021; Touitou et al., 2017). From an environmental perspective, these results reinforce concerns about light intrusion during sleep time at night in residential and institutional settings.

In contrast to nighttime exposure, melanopic EDI exposure during the morning hours was consistently associated with beneficial outcomes across multiple mood-related symptoms. Higher exposure around 10:00 a.m. was linked to lower sadness and sleepiness and to higher concentration, energy, appetite, and well-being, indicating that light exposure during this circadian phase exerts broad effects on mood regulation. These findings align with evidence from both clinical and non-clinical populations demonstrating the benefits of morning light exposure (Benedetti et al., 2001; Bonatto et al., 2024; Esaki et al., 2021; Figueiro et al., 2017; Wirz-Justice et al., 1996). Also, studies indicate that light therapy has a greater impact on mood symptoms when administered in the early morning hours (Terman et al., 2001; Wirz-Justice & Terman, 2022), and that responses to light may vary across time and circadian phase (St Hilaire et al., 2022). Supporting this temporal specificity in everyday settings, Pilz et al. (2021) reported that higher median light exposure between 8:00 and 10:00 a.m. was associated with lower levels of depressive symptoms in rural communities. Together, these findings are consistent with the role of light in modulating mood via circadian mechanisms (Boivin et al., 1996), as well as through direct neural pathways, given that ipRGCs project to brain regions such as the lateral habenula, which is closely linked to sadness and depression (Hattar et al., 2006; Hu et al., 2020).

Beyond reinforcing the benefits of morning light, this study shows that positive effects occurred as long as participants were exposed to light shortly after awakening, regardless of clock time. Exposure to melanopic EDI $\geq$ 250 lx after wake-up was associated with improvements across all analysed outcomes; notably, more than 15 min of exposure shortly after awakening was sufficient to improve levels of sadness, anxiety, sleepiness, and well-being. This temporal flexibility supports emerging evidence on individual differences in circadian light sensitivity (Vetter et al., 2022) and may be particularly relevant for late-type individuals, as it suggests that beneficial light exposure can be timed relative to individual wake timing rather than requiring earlier wake times. In addition, our results overall indicate that when light exposure occurs closer to wake-up time, a shorter exposure duration is needed to achieve the same benefits for mood and well-being. This finding has clear practical relevance for everyday environments, where access to daylight or high illuminance varies considerably.

The cumulative within-subject patterns observed after wake-up indicate that the effects of melanopic EDI on sleepiness, concentration, energy, and well-being strengthen as both exposure duration and intensity increase. This dose–response pattern is consistent with the intensity-dependent nature of melanopsin-mediated responses (Brown, 2020; de Zeeuw et al., 2019) and aligns with everyday-life findings showing reduced subjective sleepiness while awake with higher melanopic EDI exposure (Didikoglu et al., 2023). While the role of light in modulating alertness (or reducing sleepiness, often considered indicative of reduced alertness) is well established (Cajochen, 2007; Lok et al., 2018; Siraji et al., 2022; Souman et al., 2018), the present findings extend this literature by highlighting associations with perceived concentration and energy–dimensions of mood that have been comparatively underexplored in everyday life light exposure studies.

Contrary to expectations, greater exposure to melanopic EDI $>$ 10 lx within the 3 h before sleep was associated with higher subsequent concentration, energy, and well-being. Similar unexpected findings have been reported by Didikoglu et al. (2023), who observed that greater exposure to light exceeding the recommended exposure before sleep was associated with an earlier sleep time. In our study, these effects appeared to be influenced by individual variation (within-subject effects). While evening light exposure generally has the potential to disrupt circadian rhythms, recent evidence indicates notable individual differences in this response, which likely arise from variations within the retina and downstream pathways, including the central circadian clock (Chellappa, 2020; Phillips et al., 2019). A study conducted by te Kulve et al. (2019) demonstrated that early-evening exposure to bright light might mitigate some sleep-disruptive effects of later evening light, further highlighting the variability in the potential impacts of evening light exposure. Furthermore, Schöllhorn et al. (2023) reported that individuals showed greater sensitivity to evening light during shorter photoperiods, affecting the response of the melanopsin system and influencing human sleep. However, their study was conducted in the Northern Hemisphere, where seasonal variations in photoperiod are pronounced, in contrast with our research in Brazilian cities (e.g., Porto Alegre, 30.04°S, and São Paulo, 23.56°S), where seasonal variation in daytime light hours is substantially smaller. In addition, although the focus of the present study is light exposure, such exposures occur within a broader social context that can significantly influence mood and well-being (Tonon et al., 2024). Even during periods of COVID-19 social distancing, individuals engaged in alternative forms of social interaction (Barbeau



(caption on next page)

Fig. 5. Within-subject results from separate robust linear mixed–effects regression models for each different exposure duration threshold in the interval (3 h before sleep, during nighttime while sleeping, and within 1 h, 2 h, and 3 h after wake-up) and outcome. The number of days or nights in which melanopic EDI exposure meets daytime or exceeds nighttime recommendations (threshold values are shown at the top of the plots) for at least 15, 30, 60, 90, and 120 min was assessed over rolling 7-day intervals. Mood-related symptoms (MRh–RD: Mood Rhythm Reduced Diary) and well-being scores (WHO-5: Five-item World Health Organization Well-Being Index) were also averaged across 7-day rolling intervals. Mood-related symptoms and well-being scores were regressed on the duration and frequency of melanopic EDI exposure over the same weekly intervals (cross-sectional analysis). The seven top plots display changes in each outcome compared with 0 days meeting the melanopic EDI thresholds. Grey–shaded rectangles indicate associations with subsequent outcomes; yellow–shaded rectangles indicate associations with same–day outcomes. Analyses were adjusted for sex, age, and midpoint of sleep. Models for duration and frequency with predictors during the nighttime (grey–shaded rectangles) were further adjusted for the relative ratio of melanopic EDI exposure durations within the entire daytime and the analysed period at night (RDLE: relative duration of light exposure). The bottom plot shows the average number of days or nights per 7-day interval in which melanopic EDI exposure met the recommended values for at least 15, 30, 60, 90, and 120 min. Bars represent the mean, and error bars indicate one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2024; Malighetti et al., 2023; Norcia et al., 2022). Therefore, higher evening melanopic EDI exposure may reflect concurrent activities or contextual factors that contribute to subsequent outcomes, rather than light exposure alone. Future studies should investigate the combined effects of multiple *zeitgebers* during the 3 h preceding sleep onset on subsequent well-being.

One factor that may contribute to the heterogeneous findings in the literature relates to how current light exposure recommendations are defined and applied. Existing guidelines specify a maximum exposure level of 10 lx melanopic EDI in the evening (within 3 h before bedtime), a maximum exposure level of 1 lx melanopic EDI during the nighttime sleep period, and a minimum continuous exposure level of 250 lx melanopic EDI during daytime (Brown et al., 2022; CIE, 2024). These recommendations are primarily derived from laboratory studies conducted in healthy adults (Brown, 2020) and have been widely adopted as reference values for promoting healthier environments. Although melanopic EDI provides a standardised framework for characterising light exposure, it represents a pragmatic simplification of complex retinal and post-retinal processes and should therefore be interpreted accordingly.

While they provide an essential framework, our findings suggest that further refinement may be needed to better account for individual variability, diverse populations, and the range of environmental contexts encountered in everyday life across different regions of the globe (CIE, 2024). Notably, our results demonstrated that participants spent limited time meeting the recommended daytime melanopic EDI threshold ($\geq$250 lx) and were frequently exposed to melanopic light levels exceeding recommended limits during the evening and night. From a public health perspective, these findings underscore the difficulty of achieving recommended melanopic EDI targets in real-world settings. The combination of insufficient daytime light exposure and excessive evening and nighttime melanopic exposure suggests that contemporary lighting environments may systematically deviate from circadian-friendly conditions, reinforcing the need for environmental and behavioural interventions that enhance daytime light exposure while minimising biologically active light at night.

This study was conducted during the COVID-19 pandemic, and although this may limit its external validity, this context provided a unique opportunity to assess the impact of light exposure on daily mood and well-being in a large sample over an extended period. Given the movement and socialization restrictions imposed during the pandemic, further research is needed to determine whether these findings can be replicated under social routines related to non-pandemic conditions and under different work environments. Moreover, elevated levels of depression, anxiety, and insomnia symptoms during the pandemic (Cénat et al., 2021) may have influenced the associations. Additionally, our sample was predominantly young, female, and highly educated, which does not represent the broader population of middle-income countries. Another limitation concerns the analytical approach: because models were fitted separately for each time interval, findings should be interpreted as overall temporal patterns of association rather than as independent comparisons between intervals. Although these models are correlated because they are based on overlapping and temporally related exposure measures, the possibility of inflation cannot be excluded. Further potential limitations concern the light exposure data recorded by the wrist actigraphy device: (a) there was a risk of occlusion of the light sensor by sleeves and bedclothes, which could lead to underestimation of light exposure; (b) the wrist device does not effectively capture light that reaches the retina. In addition, melanopic EDI was estimated using three broadband sensors, which provide limited spectral resolution compared to spectroradiometric instruments.

The assessment of multiple outcomes, including symptoms such as anxiety, sadness, appetite, sleepiness, concentration, and energy, allows for a holistic analysis of the relationship between EDI exposure and mental health, as it addresses different dimensions of mood disorders. Collecting mood-related symptom data retrospectively, based on daily recollections of five different times of the day, presents both strengths and limitations. Answering once per day facilitated participant adherence and enabled a larger number of participants to complete the study. While self-reporting captures participants' subjective perceptions, it may also be susceptible to memory bias. Another limitation concerns variability in the timing of questionnaire completion, although excluding entries submitted more than 48 h after awakening produced results similar to those of the main models. Regarding the five within-day time points, a time-of-day variation in mood was expected (Boivin et al., 1997; Bu et al., 2025; Peres et al., 2011; Scheer & Chellappa, 2024), possibly due to the retrospective assessment (at the end of each day); we found minimal variation between time-point level reports (Nexha et al., 2024). Here, we evaluated the mean of the daily measures, but future studies using momentary data collected via an app developed by our team are planned. It is important to note that the symptoms assessed, such as anxiety and sadness, are commonly associated with mood disorders, which further emphasizes the clinical relevance of the study.

An important strength in this study's methodology is monitoring melanopic EDI exposure for up to 44 days. The study length allowed for assessing variations over an extended period, enabling us to analyse the impacts of light exposure over different environmental contexts and lighting conditions. Additionally, the use of a wrist-worn actigraphy device facilitates non-invasive and continuous data collection. Combining three of the device's light sensors, each with a distinct spectral response, provides a practical solution for measuring melanopic EDI exposure while accounting for the complexity of the diverse lighting conditions to which individuals may be exposed. Although these sensors have limited spectral resolution, this approach enables a more detailed assessment of light characteristics that may influence mood and well-being. Devices with higher spectral resolution and a greater number of spectral bands may improve measurement accuracy; however, they would not overcome limitations inherent to everyday-life study designs. Such designs can characterise light exposure patterns, but pathway-related metrics remain indirect approximations and are not intended to directly resolve the neural mechanisms through which light affects the brain. Future studies should consider the circadian aspect of the phenomenon under investigation, including the effects of different exposure thresholds across the day. Further research is also needed to develop scalable measures for use across different geographic contexts and everyday-life settings, including questionnaire-based approaches, while improving the assessment of individuals' perceptions of light

exposure.

Our study aligns with ongoing efforts to standardise methods and measures for assessing personal light exposure in everyday-life settings (Didikoglu et al., 2023; Hartmeyer et al., 2022; Price et al., 2012, 2017; Zauner, Hartmeyer, & Spitschan, 2024). Such efforts are essential to improve comparability across studies, increase statistical power (Zauner, Udovicic, & Spitschan, 2024), Zauner, Udovicic, & Spitschan, 2024nd support the development of evidence-based recommendations for optimal individual patterns of light exposure (Webler et al., 2019), considering quantity, timing, duration, and frequency of melanopic EDI exposure. From an architectural and environmental perspective, these results emphasize that lighting design should not only minimise harmful nighttime exposure but also actively support timely and sufficient daytime light exposure aligned with occupants' daily rhythms. Designing environments that facilitate access to adequate melanopic EDI shortly after awakening – through daylight availability, spatial configuration, and artificial lighting strategies – may represent an effective approach to promoting mental health in everyday settings.

5. Conclusion

In conclusion, this study advances methods for assessing melanopic EDI exposure in everyday life, thereby clarifying how light exposure relates to multidimensional mood symptom constructs and well-being. Our findings demonstrate that the effect of melanopic EDI varies according to the specific mood symptom, reflecting the complexity of the mood construct. In everyday environments, light exposure characteristics – such as spectrum, intensity, timing, duration, and frequency – interact simultaneously and dynamically over time, making their investigation a methodological challenge. Our methods accounted for this complexity, and our analytical approach revealed that within-subject associations were more prominent than between-subject associations, underscoring the importance of distinguishing intra-individual from inter-individual patterns and avoiding overgeneralisation of group-level findings, given the substantial variability in light exposure levels and temporal patterns across individuals.

These findings highlight individual variability as a crucial consideration in designing lighting strategies for the built environment and in developing light exposure recommendations. By identifying relevant timescales at which light exposure may enhance mood and support well-being, this study represents a step toward optimising melanopic EDI exposure throughout the day. Translating this knowledge into design strategies and architectural principles is central to the development of healthier lighting environments. Lighting design strategies that usually prioritize visual aspects, such as clarity, comfort, and aesthetics, should also consider light as a tool for health and well-being. Importantly, electric light does not inherently disrupt circadian rhythms or adversely affect mood, well-being, and sleep; rather, such effects arise when lighting is poorly designed or improperly used. Finally, the multidisciplinary nature of our research team enabled refined and optimised methodological approaches and interpretations, strengthening the relevance of our findings for mental health promotion and evidence-based lighting design.

CRediT authorship contribution statement

Fernanda S. Bonatto: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ricardo R.B. Correia:** Writing – review & editing, Methodology. **Rogério B. Borges:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Luísa K. Pilz:** Writing – review & editing, Methodology, Investigation, Data curation. **Pedro O. Macedo:** Writing – review & editing, Data curation. **Kiara Skalnes:** Writing – review & editing. **Marco Idiart:** Writing – review & editing, Validation. **Fernanda G. Amaral:** Writing – review & editing, Investigation. **Maria Paz Hidalgo:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Ethics declaration

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place. This study was approved by the Comissão Nacional de Ética em Pesquisa – CONEP. (Approval No. CAAE 30396320.1.0000.5327)

Conflict of interest

The authors declare they have no conflicts of interest related to this work to disclose.

Acknowledgments

This study was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), finance code 001 (CAPES–Epidemias – Telemedicina e Análise de Dados Médicos, grant 88887.507070/2020–00 and 88881.507072/2020–01) and by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq MCTI FNDCT N° 22/2024 – 444100/2024-5). We are grateful to CAPES (POM), CAPES–-PRINT (MPH: 88887.717202/2022–00), CNPq (MPH: PQ – 2022: 303288/2022–1 and CNPq N° 26/2021: 402176/2022–7), and Fulbright Program (KS) for fellowships.

Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2026.103192.

References

aan het Rot, M., Moskowitz, D. S., & Young, S. N. (2008). Exposure to bright light is associated with positive social interaction and good mood over short time periods: A naturalistic study in mildly seasonal people. *Journal of Psychiatric Research, 42*(4), 311–319. https://doi.org/10.1016/j.jpsychires.2006.11.010

Alves Braga de Oliveira, M., de Mendonça Filho, E. J., Carissimi, A., Lima Dos Santos Garay, L., Scop, M., Ruschel Bandeira, D., Gutiérrez Carvalho, F., Mathur, S., Epifano, K., Adan, A., Frey, B. N., & Hidalgo, M. P. (2021). The revised mood rhythm instrument: A large multicultural psychometric study. *Journal of Clinical Medicine, 10*, 388. https://doi.org/10.3390/jcm10030388

Amaral, F. G. do, & Cipolla-Neto, J. (2018). A brief review about melatonin, a pineal hormone. *Archives of Endocrinology and Metabolism, 62*, 472–479. https://doi.org/10.20945/2359-3997000000066

Aschoff, J. (1960). Exogenous and endogenous components in circadian rhythms. *Cold Spring Harbor Symposia on Quantitative Biology, 25*, 11–28. https://doi.org/10.1101/sqb.1960.025.01.004

Barbeau, A. K., Héroux, I., Ryan, G., & Thouin-Poppe, L.É. (2024). The effects of musical practice on the well-being, mental health and social support of student, amateur, and professional musicians in Canada during the COVID-19 pandemic. *Frontiers in Psychology, 15*, Article 1386229. https://doi.org/10.3389/fpsyg.2024.1386229

Baron, K. G., Reid, K. J., Kern, A. S., & Zee, P. C. (2011). Role of sleep timing in caloric intake and BMI. *Obesity, 19*, 1374–1381. https://doi.org/10.1038/oby.2011.100

Benedetti, F., Colombo, C., Barbini, B., Campori, E., & Smeraldi, E. (2001). Morning sunlight reduces length of hospitalization in bipolar depression. *Journal of Affective Disorders, 62*, 221–223. https://doi.org/10.1016/S0165-0327(00)00149-X

Böhmer, M. N., Hamers, P. C. M., Bindels, P. J. E., Oppewal, A., Someren, E. J. W. van, & Festen, D. A. M. (2021). Are we still in the dark? A systematic review on personal daily light exposure, sleep-wake rhythm, and mood in healthy adults from the general population. *Sleep Health: Journal of the National Sleep Foundation, 7*, 610–630. https://doi.org/10.1016/j.sleh.2021.06.001

Boivin, D. B., Czeisler, C. A., Dijk, D. J., Duffy, J. F., Folkard, S., Minors, D. S., Totterdell, P., & Waterhouse, J. M. (1997). Complex interaction of the sleep-wake cycle and circadian phase modulates mood in healthy subjects. *Archives of General Psychiatry, 54*, 145–152. https://doi.org/10.1001/archpsyc.1997.01830140055010

Boivin, D. B., Duffy, J. F., Kronauer, R. E., & Czeisler, C. A. (1996). Dose-response relationships for resetting of human circadian clock by light. *Nature, 379*, 540–542. https://doi.org/10.1038/379540a0

Bonatto, F. S., Pilz, L. K., Borges, R. B., Xavier, N. B., Tonon, A. C., do Amaral, F. G., & Hidalgo, M. P. L. (2024). Daylight exposure and mood in real life: Direct association

and mediating role of sleep and routine regularity. *Chronobiology International, 41*, 1128–1141. https://doi.org/10.1080/07420528.2024.2381590
Brainard, G. C., Hanifin, J. P., Greeson, J. M., Byrne, B., Glickman, G., Gerner, E., & Rollag, M. D. (2001). Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor. *Journal of Neuroscience, 21*, 6405–6412. https://doi.org/10.1523/JNEUROSCI.21-16-06405.2001
Brown, T. M. (2020). Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. *Journal of Pineal Research, 69*, Article e12655. https://doi.org/10.1111/jpi.12655
Brown, T. M., Brainard, G. C., Cajochen, C., Czeisler, C. A., Hanifin, J. P., Lockley, S. W., Lucas, R. J., Münch, M., O'Hagan, J. B., Peirson, S. N., Price, L. L. A., Roenneberg, T., Schlangen, L. J. M., Skene, D. J., Spitschan, M., Vetter, C., Zee, P. C., & Jr, K. P. W. (2022). Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. *PLoS Biology, 20*, Article e3001571. https://doi.org/10.1371/journal.pbio.3001571
Bu, F., Bone, J. K., & Fancourt, D. (2025). Will things feel better in the morning? A time-of-day analysis of mental health and wellbeing from nearly 1 million observations. *BMJ Ment Health, 28*. https://doi.org/10.1136/bmjment-2024-301418
Burns, A. C., Windred, D. P., Rutter, M. K., Olivier, P., Vetter, C., Saxena, R., Lane, J. M., Phillips, A. J. K., & Cain, S. W. (2023). Day and night light exposure are associated with psychiatric disorders: An objective light study in >85,000 people. *Nature Mental Health, 1*. https://doi.org/10.1038/s44220-023-00135-8
Cajochen, C. (2007). Alerting effects of light. *Sleep Medicine Reviews, 11*, 453–464. https://doi.org/10.1016/j.smrv.2007.07.009
Castillo, J., Tonon, A. C., Hidalgo, M. P., Silva, A., & Tassino, B. (2023). Individual light history matters to deal with the Antarctic summer. *Scientific Reports, 13*, 12081. https://doi.org/10.1038/s41598-023-39315-y
Cénat, J. M., Blais-Rochette, C., Kokou-Kpolou, C. K., Noorishad, P.-G., Mukunzi, J. N., McIntee, S.-E., Dalexis, R. D., Goulet, M.-A., & Labelle, P. R. (2021). Prevalence of symptoms of depression, anxiety, insomnia, posttraumatic stress disorder, and psychological distress among populations affected by the COVID-19 pandemic: A systematic review and meta-analysis. *Psychiatry Research, 295*, Article 113599. https://doi.org/10.1016/j.psychres.2020.113599
Chang, A.-M., Scheer, F. A. J. L., & Czeisler, C. A. (2011). The human circadian system adapts to prior photic history. *The Journal of Physiology, 589*, 1095–1102. https://doi.org/10.1113/jphysiol.2010.201194
Chellappa, S. L. (2020). Individual differences in light sensitivity affect sleep and circadian rhythms. *Sleep, 44*, Article zsaa214. https://doi.org/10.1093/sleep/zsaa214
Cho, Y., Ryu, S.-H., Lee, B. R., Kim, K. H., Lee, E., & Choi, J. (2015). Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment. *Chronobiology International, 32*, 1294–1310. https://doi.org/10.3109/07420528.2015.1073158
Commission Internationale de l'Eclairage (CIE). (2018). *CIE system for metrology of optical radiation for ipRGC-influenced responses to light (CIE S026/E:2018)*. Vienna, Austria: CIE. https://doi.org/10.25039/S026.2018
Commission Internationale de l'Eclairage (CIE). (2020). *CIE S026 α-opic toolbox*. CIE. https://doi.org/10.25039/S026.2018.TB. Version v1.049.
Commission Internationale de l'Eclairage (CIE). (2024). *Position statement on integrative lighting - Recommending proper light at the proper time (PS 001:2024)*. Vienna, Austria: Commission Internationale de l'Eclairage. https://doi.org/10.25039/PS.b2twa77g
Copenhaver, A. E., Roberts, R. C., & LeGates, T. A. (2022). Light-dependent effects on mood: Mechanistic insights from animal models. *Progress in Brain Research, 273*, 71–95. https://doi.org/10.1016/bs.pbr.2022.02.016
Dashti, H. S., Scheer, F. A. J. L., Saxena, R., & Garaulet, M. (2019). Timing of food intake: Identifying contributing factors to design effective interventions. *Advances in Nutrition, 10*, 606–620. https://doi.org/10.1093/advances/nmy131
de Souza, C. M., & Hidalgo, M. P. L. (2012). World Health Organization 5-item well-being index: Validation of the Brazilian Portuguese version. *European Archives of Psychiatry and Clinical Neuroscience, 262*, 239–244. https://doi.org/10.1007/s00406-011-0255-x
de Zeeuw, J., Papakonstantinou, A., Nowozin, C., Stotz, S., Zaleska, M., Hädel, S., Bes, F., Münch, M., & Kunz, D. (2019). Living in biological darkness: Objective sleepiness and the pupillary light responses are affected by different metameric lighting conditions during daytime. *Journal of Biological Rhythms, 34*, 410–431. https://doi.org/10.1177/0748730419847845
Didikoglu, A., Mohammadian, N., Johnson, S., van Tongeren, M., Wright, P., Casson, A. J., Brown, T. M., & Lucas, R. J. (2023). Associations between light exposure and sleep timing and sleepiness while awake in a sample of UK adults in everyday life. *Proceedings of the National Academy of Sciences, 120*, Article e2301608120. https://doi.org/10.1073/pnas.2301608120
Esaki, Y., Obayashi, K., Saeki, K., Fujita, K., Iwata, N., & Kitajima, T. (2021). Preventive effect of morning light exposure on relapse into depressive episode in bipolar disorder. *Acta Psychiatrica Scandinavica, 143*, 328–338. https://doi.org/10.1111/acps.13287
Esaki, Y., Obayashi, K., Saeki, K., Fujita, K., Iwata, N., & Kitajima, T. (2022). Effect of nighttime bedroom light exposure on mood episode relapses in bipolar disorder. *Acta Psychiatrica Scandinavica, 146*, 64–73. https://doi.org/10.1111/acps.13422
Figueiro, M. G., Steverson, B., Heerwagen, J., Kampschroer, K., Hunter, C. M., Gonzales, K., Plitnick, B., & Rea, M. S. (2017). The impact of daytime light exposures on sleep and mood in office workers. *Sleep Health, 3*, 204–215. https://doi.org/10.1016/j.sleh.2017.03.005
Green, P., & MacLeod, C. J. (2016). SIMR: An R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution, 7*, 493–498. https://doi.org/10.1111/2041-210X.12504
Hartmeyer, S. L., Webler, F. S., & Andersen, M. (2022). Towards a framework for light-dosimetry studies: Methodological considerations. *Lighting Research and Technology*. https://doi.org/10.1177/14771535221103258
Hattar, S., Kumar, M., Park, A., Tong, P., Tung, J., Yau, K.-W., & Berson, D. M. (2006). Central projections of melanopsin-expressing retinal ganglion cells in the mouse. *Journal of Comparative Neurology, 497*, 326–349. https://doi.org/10.1002/cne.20970
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*, 198–203. https://doi.org/10.1034/j.1600-079X.2002.01885.x
Hu, H., Cui, Y., & Yang, Y. (2020). Circuits and functions of the lateral habenula in health and in disease. *Nature Reviews Neuroscience, 21*, 277–295. https://doi.org/10.1038/s41583-020-0292-4
Hubalek, S., Brink, M., & Schierz, C. (2010). Office workers daily exposure to light and its influence on sleep quality and mood. *Lighting Research and Technology, 42*(1), 33–50. https://doi.org/10.1177/1477153509355632
Knoop, M., Stefani, O., Bueno, B., Matusiak, B., Hobday, R., Wirz-Justice, A., Martiny, K., Kantermann, T., Aarts, M., Zemmouri, N., Appelt, S., & Norton, B. (2020). Daylight: What makes the difference? *Lighting Research and Technology, 52*, 423–442. https://doi.org/10.1177/1477153519869758
Koller, M. (2016). Robustlmm: An R package for robust estimation of linear mixed-effects models. *Journal of Statistical Software, 75*, 1–24. https://doi.org/10.18637/jss.v075.i06
LeGates, T. A., Fernandez, D. C., & Hattar, S. (2014). Light as a central modulator of circadian rhythms, sleep and affect. *Nature Reviews Neuroscience, 15*, 443–454. https://doi.org/10.1038/nrn3743
Lenth, R. V., Banfai, B., Bolker, B., Buerkner, P., Giné-Vázquez, I., Herve, M., Jung, M., Love, J., Miguez, F., Piaskowski, J., Riebl, H., & Singmann, H. (2025). *Emmeans: Estimated marginal means, aka least-squares means*.
Lok, R., Smolders, K. C. H. J., Beersma, D. G. M., & de Kort, Y. A. W. (2018). Light, alertness, and alerting effects of white light: A literature overview. *Journal of Biological Rhythms, 33*, 589–601. https://doi.org/10.1177/0748730418796443
Lucassen, E. A., Zhao, X., Rother, K. I., Mattingly, M. S., Courville, A. B., de Jonge, L., Csako, G., & Cizza, G. (2013). Evening chronotype is associated with changes in eating behavior, more sleep apnea, and increased stress hormones in short sleeping Obese individuals. *PLoS One, 8*, Article e56519. https://doi.org/10.1371/journal.pone.0056519
Lüdecke, D. (2018). Ggeffects: Tidy data frames of marginal effects from regression models. *Journal of Open Source Software, 3*, 772. https://doi.org/10.21105/joss.00772
Malighetti, C., Bernardelli, L., Pancini, E., Riva, G., & Villani, D. (2023). Promoting emotional and psychological well-being during COVID-19 pandemic: A self-help virtual reality intervention for university students. *Cyberpsychology, Behavior, and Social Networking*, 10.1089_cyber.2022.0246.
Maukonen, M., Kanerva, N., Partonen, T., Kronholm, E., Tapanainen, H., Kontto, J., & Männistö, S. (2017). Chronotype differences in timing of energy and macronutrient intakes: A population-based study in adults. *Obesity, 25*, 608–615. https://doi.org/10.1002/oby.21747
Muñoz, J. S. G., Cañavate, R., Hernández, C. M., Cara-Salmerón, V., & Morante, J. J. H. (2017). The association among chronotype, timing of food intake and food preferences depends on body mass status. *European Journal of Clinical Nutrition, 71*, 736–742. https://doi.org/10.1038/ejcn.2016.182
Nexha, A., Pilz, L. K., Oliveira, M. A. B., Xavier, N. B., Borges, R. B., Frey, B. N., & Hidalgo, M. P. L. (2024). Greater within- and between-day instability is associated with worse anxiety and depression symptoms. *Journal of Affective Disorders, 356*, 215–223. https://doi.org/10.1016/j.jad.2024.04.014
Nixon, A., Robillard, R., Leveille, C., Douglass, A. B., Porteous, M., & Veitch, J. A. (2023). Assessing the effects of polychromatic light exposure on mood in adults: A systematic review contrasting α-opic equivalent daylight illuminances. *Leukos, 20*(2), 127–147. https://doi.org/10.1080/15502724.2023.2219017
Norcia, A. D., Mascaro, C., Bianchi, D., Szpunar, G., & Cannoni, E. (2022). Adolescent psychological well-being during the COVID-19 lockdown: The role of leisure activities and online peer communication. *Current Psychology, 1*. https://doi.org/10.1007/s12144-022-03679-7
Obayashi, K., Tai, Y., Yamagami, Y., & Saeki, K. (2022). Associations between indoor light pollution and unhealthy outcomes in 2,947 adults: Cross-sectional analysis in the HEIJO-KYO cohort. *Environmental Research, 215*, Article 114350. https://doi.org/10.1016/j.envres.2022.114350
Peres, I., Vetter, C., Blautzik, J., Reiser, M., Pöppel, E., Meindl, T., Roenneberg, T., & Gutyrchik, E. (2011). Chronotype predicts activity patterns in the neural underpinnings of the motor system during the day. *Chronobiology International, 28*, 883–889. https://doi.org/10.3109/07420528.2011.619084
Phillips, A. J. K., Vidafar, P., Burns, A. C., McGlashan, E. M., Anderson, C., Rajaratnam, S. M. W., Lockley, S. W., & Cain, S. W. (2019). High sensitivity and interindividual variability in the response of the human circadian system to evening light. In *Proceedings of the National Academy of Sciences, 116* pp. 12019–12024). https://doi.org/10.1073/pnas.1901824116
Pilz, L. K., de Oliveira, M. A. B., Steibel, E. G., Policarpo, L. M., Carissimi, A., Carvalho, F. G., Constantino, D. B., Tonon, A. C., Xavier, N. B., da Rosa Righi, R., & Hidalgo, M. P. (2022). Development and testing of methods for detecting off-wrist in actimetry recordings. *Sleep, 45*, Article zsac118. https://doi.org/10.1093/sleep/zsac118
Pilz, L. K., Xavier, N. B., Levandovski, R., Oliveira, M. A. B., Tonon, A. C., Constantino, D. B., Machado, V., Roenneberg, T., & Hidalgo, M. P. (2021). Circadian strain, light exposure, and depressive symptoms in rural communities of southern

Brazil. *Front Netw Physiol, 1*, Article 779136. https://doi.org/10.3389/fnetp.2021.779136
Price, L., Khazova, M., & O'Hagan, J. (2012). Performance assessment of commercial circadian personal exposure devices. *Lighting Research and Technology, 44*, 17–26. https://doi.org/10.1177/1477153511433171
Price, L. L. A., Lyachev, A., & Khazova, M. (2017). Optical performance characterization of light-logging actigraphy dosimeters. *ournal of the Optical Society of America A JOSAA, 34*, 545–557. https://doi.org/10.1364/JOSAA.34.000545
Rahman, S. A., St Hilaire, M. A., & Lockley, S. W. (2017). The effects of spectral tuning of evening ambient light on melatonin suppression, alertness and sleep. *Physiology & Behavior, 177*, 221–229. https://doi.org/10.1016/j.physbeh.2017.05.002
Ralph, M. R., Foster, R. G., Davis, F. C., & Menaker, M. (1990). Transplanted suprachiasmatic nucleus determines circadian period. *Science, 247*, 975–978. https://doi.org/10.1126/science.2305266
Refinetti, R. (2019). Chronotype variability and patterns of light exposure of a large cohort of United States residents. *Yale J Biol Med, 92*, 179–186.
Reiter, R. J. (2003). Melatonin: Clinical relevance. Best practice & research clinical endocrinology & metabolism. *Endocrinology and Lifestyle, 17*, 273–285. https://doi.org/10.1016/S1521-690X(03)00016-2
Scheer, F. A. J. L., & Chellappa, S. L. (2024). Endogenous circadian rhythms in mood and well-being. *Sleep Health, Festschrift of Dr. Charles A. Czeisler, 10*, S149–S153. https://doi.org/10.1016/j.sleh.2023.07.012
Scheer, F. A. J. L., Morris, C. J., & Shea, S. A. (2013). The internal circadian clock increases hunger and appetite in the evening independent of food intake and other behaviors. *Obesity, 21*, 421–423. https://doi.org/10.1002/oby.20351
Schöllhorn, I., Stefani, O., Blume, C., & Cajochen, C. (2023). Seasonal variation in the responsiveness of the melanopsin system to evening light: Why we should report season when collecting data in human sleep and circadian studies. *Clocks Sleep, 5*, 651–666. https://doi.org/10.3390/clockssleep5040044
Siraji, M. A., Kalavally, V., Schaefer, A., & Haque, S. (2022). Effects of daytime electric light exposure on human alertness and higher cognitive functions: A systematic review. *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.765750
Smith, K. A., Schoen, M. W., & Czeisler, C. A. (2004). Adaptation of human pineal melatonin suppression by recent photic history. *Journal of Clinical Endocrinology and Metabolism, 89*, 3610–3614. https://doi.org/10.1210/jc.2003-032100
Smolders, K. C. H. J., de Kort, Y. A. W., & van den Berg, S. M. (2013). Daytime light exposure and feelings of vitality: Results of a field study during regular weekdays. *Journal of Environmental Psychology, 36*(0), 270–279. https://doi.org/10.1016/j.jenvp.2013.09.004
Souman, J. L., Tinga, A. M., te Pas, S. F., van Ee, R., & Vlaskamp, B. N. S. (2018). Acute alerting effects of light: A systematic literature review. *Behavioural Brain Research, 337*, 228–239. https://doi.org/10.1016/j.bbr.2017.09.016
St Hilaire, M. A., Ámundadóttir, M. L., Rahman, S. A., Rajaratnam, S. M. W., Rüger, M., Brainard, G. C., Czeisler, C. A., Andersen, M., Gooley, J. J., & Lockley, S. W. (2022). The spectral sensitivity of human circadian phase resetting and melatonin suppression to light changes dynamically with light duration. *Proceedings of the National Academy of Sciences, 119*, Article e2205301119. https://doi.org/10.1073/pnas.2205301119
te Kulve, M., Schlangen, L. J. M., & van Marken Lichtenbelt, W. D. (2019). Early evening light mitigates sleep compromising physiological and alerting responses to subsequent late evening light. *Scientific Reports, 9*, 16064. https://doi.org/10.1038/s41598-019-52352-w
Terman, J. S., Terman, M., Lo, E.-S., & Cooper, T. B. (2001). Circadian time of morning light administration and therapeutic response in winter depression. *Archives of General Psychiatry, 58*, 69–75. https://doi.org/10.1001/archpsyc.58.1.69
Thapan, K., Arendt, J., & Skene, D. J. (2001). An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans. *The Journal of Physiology, 535*, 261–267. https://doi.org/10.1111/j.1469-7793.2001.t01-1-00261.x
Tonon, A. C., Abreu, A. C. O. V., Silva, M. M. D., Tavares, P. S., Nishino, F., Versignassi, P., Amando, G. R., Constantino, D. B., Pilz, L. K., Steibel, E., Suchecki, D., Amaral, F. G. D., & Hidalgo, M. P. (2024). Human social isolation and stress: A systematic review of different contexts and recommendations for future studies. *Trends Psychiatry Psychother, 46*, Article e20210452. https://doi.org/10.47626/2237-6089-2021-0452
Tonon, A. C., Constantino, D. B., Amando, G. R., Abreu, A. C., Francisco, A. P., de Oliveira, M. A. B., Pilz, L. K., Xavier, N. B., Rohrsetzer, F., Souza, L., Piccin, J., Caye, A., Petresco, S., Manfro, P. H., Pereira, R., Martini, T., Kohrt, B. A., Fisher, H. L., Mondelli, V., Kieling, C., & Hidalgo, M. P. L. (2022). Sleep disturbances, circadian activity, and nocturnal light exposure characterize high risk for and current depression in adolescence. *Sleep, 45*, Article zsac104. https://doi.org/10.1093/sleep/zsac104
Tonon, A. C., Pilz, L. K., Markus, R. P., Hidalgo, M. P., & Elisabetsky, E. (2021). Melatonin and depression: A translational perspective from animal models to clinical studies. *Frontiers in Psychiatry, 12*, Article 638981. https://doi.org/10.3389/fpsyt.2021.638981
Topp, C. W., Østergaard, S. D., Søndergaard, S., & Bech, P. (2015). The WHO-5 well-being index: A systematic review of the literature. *Psychotherapy and Psychosomatics, 84*, 167–176. https://doi.org/10.1159/000376585
Touitou, Y., Reinberg, A., & Touitou, D. (2017). Association between light at night, melatonin secretion, sleep deprivation, and the internal clock: Health impacts and mechanisms of circadian disruption. *Life Sciences, 173*, 94–106. https://doi.org/10.1016/j.lfs.2017.02.008
van de Pol, M., & Wright, J. (2009). A simple method for distinguishing within- versus between-subject effects using mixed models. *Animal Behaviour, 77*, 753–758. https://doi.org/10.1016/j.anbehav.2008.11.006
Vetter, C., Pattison, P. M., Houser, K., Herf, M., Phillips, A. J. K., Wright, K. P., Skene, D. J., Brainard, G. C., Boivin, D. B., & Glickman, G. (2022). A review of human physiological responses to light: Implications for the development of integrative lighting solutions. *Leukos, 18*, 387–414. https://doi.org/10.1080/15502724.2021.1872383
Webler, F. S., Spitschan, M., Foster, R. G., Andersen, M., & Peirson, S. N. (2019). What is the 'spectral diet' of humans? *Current Opinion in Behavioral Sciences, 30*, 80–86. https://doi.org/10.1016/j.cobeha.2019.06.006
Weil, T., Daly, K. M., Yarur Castillo, H., Thomsen, M. B., Wang, H., Mercau, M. E., Hattar, S., Tejeda, H., & Fernandez, D. C. (2022). Daily changes in light influence mood via inhibitory networks within the thalamic perihabenular nucleus. *Science Advances, 8*, Article eabn3567. https://doi.org/10.1126/sciadv.abn3567
Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. New York: Springer-Verlag.
Wirz-Justice, A., Graw, P., Kräuchi, K., Sarrafzadeh, A., English, J., Arendt, J., & Sand, L. (1996). 'Natural' light treatment of seasonal affective disorder. *Journal of Affective Disorders, 37*, 109–120. https://doi.org/10.1016/0165-0327(95)00081-X
Wirz-Justice, A., Skene, D., & Münch, M. (2020). The relevance of daylight for humans. *Biochemical Pharmacology, 191*, Article 114304. https://doi.org/10.1016/j.bcp.2020.114304
Wirz-Justice, A., & Terman, M. (2022). CME: Light therapy: Why, what, for whom, how, and when (and a postscript about darkness). *Praxis*.
Wutzler, T. (2021). *Solartime: Utilities dealing with solar time such as sun position and time of sunrise*.
Zauner, J., Hartmeyer, S., & Spitschan, M. (2024a). LightLogR: Reproducible analysis of personal light exposure data with an open-source. *R package*. https://doi.org/10.31219/osf.io/qk924
Zauner, J., Udovicic, L., & Spitschan, M. (2024b). Power analysis for personal light exposure measurements and interventions. *PLoS One, 19*, Article e0308768. https://doi.org/10.1371/journal.pone.0308768