Tracking human light exposure, health and wellbeing using data-logging sensors and smartwatches—a pilot study

Nazanin Ganjehzadeh[1], J. Alstan Jakubiec[1]
[1]University of Toronto, Ontario, Canada

Abstract

This paper presents a novel data collection methodology for tracking and analyzing human light exposure and its subsequent impact on health and wellbeing. Data-logging, worn spectral irradiance sensors and smartwatch-administered surveys are used to gather timeseries spectral irradiance and qualitative data to assess the impacts of light exposure on sleep quality, mood, and alertness. By capturing the varied light exposure experienced by individuals in various environments with qualitative self-reported wellbeing measures, we begin to unravel the 'room versus human' relationship. The aim of applying this methodology to broader population-based research is to unearth patterns and insights that inform our understanding of light exposure's role in different contexts, potentially guiding adjustments to daily living environments for enhanced circadian health. The resulting data will serve as a groundwork for future large-scale applications and sets the stage for in-depth exploration into the personalized effects of light, contributing to the discourse on human-centric lighting strategies.

Introduction

Quantifying light's impact on human health and wellbeing stands is a crucial challenge. Recent advancements bring to light non-visual effects of our illuminated environments. For example, light exposure plays a critical role in regulating our circadian rhythms, influencing sleep quality, and maintaining our overall physiological state mediated by intrinsically photosensitive retinal ganglion cells (ipRGCs). ipRGCs are a unique type of photoreceptor found in the retina responsible for a range of non-visual responses to light (Berson et al., 2002; Hattar et al., 2002; Provencio et al., 1998). This recognition has led to the development of novel methods and tools to quantify these influences (Inanici et al., 2015; International Commission on Illumination (CIE) & Schlangen, 2018; Jakubiec & Alight, 2021; Maskarenj et al., 2022; Pierson et al., 2022).

Initial studies by Zeitzer and colleagues (2000) studied the sensitivity to minimal changes in nocturnal light, revealing a relationship between light exposure and melatonin phase resetting and suppression. Andersen and colleagues (2012) introduced a photobiology-based model, proposing a framework to predict the non-visual effects of daylight. They extended this model to simulate these effects, offering a simulation process that involves assessing daylight's non-visual impact based on climate data and building orientation, providing insights into optimal building designs and window orientations for enhancing occupant health and wellbeing (Mardaljevic et al., 2014). Lucas and colleagues (2014) explored the non-visual role of light, focusing on its regulatory impact on circadian rhythms and other physiological and behavioral responses. They proposed a measurement strategy for light that considers the complex interaction of photoreceptive inputs to non-visual systems, necessitating measurement of the full spectral character of light to predict its' influence on human health and behavior.

In architectural design, Brennan (2018) explored outcome-based designs for circadian lighting, integrating simulation and nonvisual metrics in a design process. His approach considered various climatic, view, and material finish conditions, underscoring the necessity for design processes that address circadian health. Daylight-driven circadian lighting design is also found in Konis's (2019) circadian design assist tool, which evaluates daylight access in buildings for human biological lighting needs, considering the spatial and temporal aspects of light exposure that influence circadian rhythms. Jakubiec & Alight (2021) introduced a simulation system for daylight and electrical lighting, enabling the customization of lighting levels, control systems, and nighttime adjustments to screen devices. Their research revealed that personal lighting preferences can significantly affect melatonin suppression in the evening, daytime alertness, and pre-nighttime sleepiness levels.

Studies such as those by Webler and colleagues (2021) have highlighted the importance of accurate, personal light monitoring to assess the spectrally-resolved exposure individuals experience in their daily environments. This has opened up avenues for a deeper understanding of the 'spectral diet' of humans, moving beyond controlled laboratory conditions to more naturalistic settings (Webler et al., 2019). These sensor technologies (Hammad et al., 2024; Webler et al., 2021) serve as a testament to this

progress, aiming to bridge the gap between our existing knowledge and the data required to fully comprehend the chronobiological implications of light.

This need for refined light exposure data reflects a broader shift in focus from static architectural lighting analysis to dynamic, occupant-centric evaluations as proposed by Danell and colleagues (2020), which investigated the spatial and temporal behaviors of individuals within lit environments on circadian health metrics. The analysis workflows adapted by Danell and colleagues (2020) delve into evaluating non-visual effects of light, using metrics like Equivalent Melanopic Lux (EML) and non-visual Direct-Response (nvRD), thereby allowing us to observe how user profiles within a lit environment may differentially influence individual light exposure profiles. These methodological innovations pave the way for a more integrated approach that encapsulates the interplay of light exposure with human behavior, offering a human-centric lens by which to assess temporal light exposure.

Jayathissa and colleagues (2019) harnessed smartwatch technology to capture occupant comfort data, with their Fitbit clock-face application 'Cozie.' This tool represents a leap toward capturing real-time, large-scale comfort data with minimal intrusion, thereby maximizing the potential for meaningful occupant-centric environmental adjustments. This methodology aligns well with the emerging paradigm that appreciates the individual variance in comfort preferences (and presumably, the effects of and exposure to light exposure), moving away from the traditional one-size-fits-all models.

Nixon et al. (2024) investigated the impact of polychromatic light on mood in healthy adults, focusing on melanopic equivalent daylight illuminances (EDI). Contrary to their hypothesis, they found no significant relationship between α-opic EDI values and mood improvements. Instead, they observed that mood enhancements were more closely tied to the duration and timing of light exposure, although these effects were not consistent across the dataset. Light's influence on mood is complex, and future research should further investigate the role of light spectrum, intensity, timing and duration on mood.

Our study seeks to explore the temporal and spatial dimensions of light exposure as mediated by human behaviour and routines with the emerging understanding of non-visual systems. In this paper, we develop and present a methodology for field measurement of ipRGC-influenced lighting on human participants regarding their self-assessed health and wellbeing. The subsequent sections outline our methodological approach which embodies a dual focus on objective measurement and subjective experience. We outline specific goals for future data analysis. Finally, specific examples of the data analysis for three participants from a pool of 15 pilot participants our methodology enables are illustrated.

Data Collection Methodology

The data collection methodology presented herein is developed to assess the relationship between spectral light exposure—due to daylight and electric lighting—and health and wellbeing indicators in individuals in real-world "field" conditions. We describe the collection and analysis methods of a comprehensive dataset that includes continuous measurements of spectral light exposure, periodic subjective impressions of health and wellbeing, and detailed records of participants' sleep-wake cycles and activity schedules. Figure 1 illustrates this data collection process.

Participants are equipped with data-logging, wearable spectral irradiance sensors and Fitbit smartwatches. These devices collect time-series spectral irradiance data and administer periodic surveys to gather both quantitative and qualitative information on participants' light exposure and their daily routines. Participants are also asked to complete a daily journal and track their activities' schedules. This comprehensive data collection aims to assess the impact of light exposure on sleep quality, mood, and alertness levels.

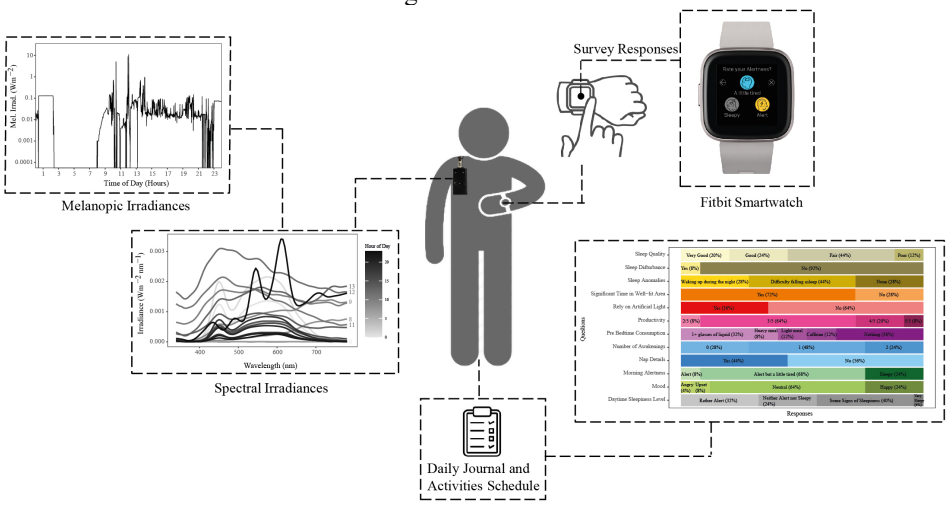

Figure 1: Data collection Process.

We employed the 'Open Optical Spectral Irradiance Sensor' (OOSI), developed by Jakubiec et al. (2022), as the primary tool for monitoring individual light exposure and evaluating electric lighting conditions within environments. The OOSI sensor, depicted in Figure 2, is worn by participants clipped to an unobtrusive location near their shirt collar, facilitating continuous data-logging of light spectrum under the dynamic conditions of human activity. The sensor measures spectral irradiance (W/m^2-nm) spanning wavelengths from 340 nm to 1,010 nm at 5 nm intervals. This capability is pivotal for assessing both photopic light levels and the spectral response of ipRGCs. It allows for the calculation of ipRGC-influenced metrics such as melanopic irradiance and melanopic EDI (equivalent daylight illuminance) under the CIE S 026 standard. The OOSI sensor's spectral specificity aids in identifying various light sources, including fluorescent light, natural daylight, and LED light as well as color temperatures. The sensor records date, time and spectral irradiance at 1-minute intervals.

Each participant is asked to wear the OOSI sensor for a period of two weeks, allowing for an assessment of participant-specific patterns and habits over a long period of time as well as the effect of discrete disruptions in their behavioural norms due to life events. The continuous spectral irradiance record is used to assess photobiological health and wellbeing metrics (Amundadottir et al., 2017; Postnova et al., 2018).

To convert the spectral irradiance data captured by the OOSI sensor into α-opic irradiances, we apply the methodology outlined by International Commission on Illumination (CIE) & Schlangen (2018) to analyze ipRGC-influenced light responses. We report melanopic irradiance (Ee,mel, W/m^2) in this manuscript which is linearly related to melanopic EDI (M-EDI lx) by a factor of ~755.

Figure 2: OOSI sensor with its clip for wearable, long-term data collection.

Participants also continuously wear a Fitbit smartwatch during the two-week data collection period. The smartwatch tracks sleep stages—such as light, deep, and REM sleep—and identifies instances of wakefulness and total sleep duration. Additionally, the smartwatch facilitated the deployment of periodic surveys. Smartwatches distributed to participants are pre-installed with a custom version of the Cozie app (Jayathissa et al., 2019) to regularly prompt participants for responses on their subjective comfort. The smartwatch with our custom 'Cozie Light' version is used to record a series of daily alertness and wellbeing questions, a subset of which is shown in Figure 3. These surveys are automatically prompted on the smartwatch four times daily at 8 AM, 12 PM, 6 PM, and 10 PM. Participants answer between 4 and 5 questions when prompted depending on the time of day. The questions focus on their current alertness, mood, recent activities, screen usage, bedroom lighting conditions, etc. Participants may also answer repeatedly at a time of their choosing. Responses are securely linked to anonymized identifiers, encrypted to ensure privacy, and automatically uploaded to a web server via a WiFi connection through a linked cell phone.

Figure 3: Sample 'Cozie Light' survey questions.

Participants complete a one-time demographic and health survey collecting basic details, including: age, gender, occupation, and lifestyle. The survey also includes questions about general health and wellbeing. As part of the data collection process, participants maintain daily journal entries on a provided spreadsheet documenting their sleep patterns, light exposure experiences, alertness levels, and general mood over the specified period. They also record their approximate locations (such as school, work, home, etc.) during each day of the two-week period at an hourly time interval.

The journals therefore collect data on participants' daily routines, behaviors and subjective experiences with light exposure and allow for an understanding of the behavior-light exposure relationship. By analyzing participants' daily journal entries, we examine how individual behaviors and environmental contexts influence light exposure throughout the day. This analysis might reveal patterns such as increased alertness following exposure to bright, natural light, or changes in mood corresponding to the transition from daylight to artificially lit environments. The documentation of sleep patterns and their alignment with natural light cycles can provide insights into participants' chronotypes, further enriching our understanding of how light exposure influences circadian rhythms and sleep quality. Moreover, the recording of general locations at hourly intervals enables us to map out the spatial dynamics

of light exposure, offering a perspective on how different environments (e.g., outdoors, home, office) impact participants' light exposure and its subsequent effects on wellbeing. This spatial-temporal mapping, combined with subjective accounts of alertness and mood, facilitates a holistic analysis of the interplay between environmental light, human behavior, and circadian health.

Analysis Plan

The aim of using the wearable sensor technology is to shift the focus of lighting analysis from static views in specific building spaces to dynamically tracking the light exposure of transient occupants. Our analysis therefore aims not only to provide individualized insights (Kim et al., 2018) but also to discern variances in light exposure among different groups of people. Distinct patterns may emerge based on factors such as the specific buildings they spend their time in and their lifestyle choices. Examining the correlations between light exposure and self-reported measures of sleep quality, productivity, and mood, offers a perspective on how architectural designs and daily routines in combination may influence light exposure, subsequently affecting the health of individuals across different environments and contexts. Our study will not only investigate the "what" and "how" of light exposure but also the "why"—the reasons behind individuals' engagement with their light environments.

This section outlines an analysis plan designed to investigate the potential correlation between actual light exposure, activity patterns, sleep patterns, and quality, as well as subjective alertness levels in daily life. Each subsection describes some of the aspects we intend to test and quantify as a pre-registration alongside some case-study examples of the analysis that our data collection makes possible using three participants with varied behavioural and light exposure patterns.

At the core of our investigation lies the question: How does the exposure to different levels of melanopic irradiance influence an individual's subjective sense of alertness, health and wellbeing? We aim to analyze the data for patterns that may reveal a direct association, proposing that as individuals experience higher levels of melanopic irradiance, they will concurrently report heightened levels of alertness. Alertness will be quantified by self-reports collected from participants via a Fitbit smartwatch, with predefined categories capturing the essence of their subjective experience: "A little tired," "Alert," and "Sleepy." These responses will be procured at four critical junctures of the day: 8 am, 12 pm, 6 pm, and 10 pm, times which are thought to capture varying degrees of environmental light exposure and circadian sensitivity.

We plan to utilize existing dynamic photobiological health models as well as mixed-effects linear regression models to assess the impacts of light on participants. This allows us to assess the relationship between the variance of melanopic irradiance (as the independent variable) and the self-reported alertness (as the dependent variable). We assess the impact of different times (day vs. night) and locations (e.g., outdoors, school, home) on melanopic irradiance levels, exploring both main effects and interaction effects. Correlation analyses will further explore how individual sleep schedules (including bedtimes and wake times) relate to alertness levels and melanopic irradiance, aiming to elucidate the role of personal lifestyle choices in health and wellbeing.

We pursue data collection until we have a comprehensive dataset spanning of 14 days for each participant. This sample size is deemed adequate to capture the variability and potential patterns of interest, and a p-value threshold of less than 0.05 will serve as our benchmark for statistical significance.

To bring our findings to life visually, we will craft scatter plots that depict the relationship between melanopic irradiance levels and alertness categories. The relative proportion of alertness reports will be denoted by the size of points on the scatter plot, providing an intuitive understanding of the data's distribution.

We anticipate that these analyses will confirm a positive association between melanopic irradiance exposure and alertness levels, albeit with notable variations due to individual and temporal/cumulative factors. We also expect to find significant variability in light exposure across locations and times, with implications for subjective wellbeing and alertness. Ultimately, this study plan seeks to highlight the importance of considering individual differences and lifestyle factors when examining the effects of light exposure on health, thereby contributing valuable insights to the fields of environmental psychology, architecture, and public health.

This pre-registration establishes a detailed and methodical blueprint for our study. It is constructed to ensure that the investigation into the relationship between ipRGC-influenced lighting and subjective alertness is not only robust and scientifically rigorous but also transparent and reproducible.

ipRGC-influenced lighting and subjective responses

Figure 4 illustrates an analysis pathway showing the relationship between average melanopic irradiance exposure (OOSI sensor) and self-reported alertness (smartwatch) at four times of a day (8 AM, 12 PM, 6 PM, and 10 PM) for three different participants with varied sleep habits and light exposure patterns. Points on the plot are color-coded to reflect three levels of reported alertness: "A little tired," "Alert," and "Sleepy." The size of each point correlates with the frequency of reported responses, implying that larger points represent more common experiences of alertness at particular times.

Our framework allows for the identification of discernible trends and fluctuations in light exposure and its impact on perceived alertness. This approach can assess the variability in participants' responses and explore how individual

circadian rhythms or schedules might affect alertness levels throughout the day. Early analysis shows that participants generally reported being "Alert" at times when they experienced higher levels of melanopic irradiance during the biological day; however, this trend is not consistent across all time periods, and participants often report being "Sleepy" despite higher irradiance exposure during afternoon and evening periods, suggesting that other homeostatic factors aside from light influence perceived alertness.

The error bars illustrate +/- 1 standard deviation indicating the variability in irradiance exposure for each time category and alertness level. Each sample participant exhibits a unique pattern of alertness throughout the day, which could be influenced by their individual schedules, natural circadian rhythms, or the specific activities they engage in at different hours. For example, in Figure 4, participant 2 shows relatively high alertness with high melanopic irradiance at 8 am, while Participants 1 and 3 reach peak alertness at 12 pm.

Future applications of this methodology should consider individual differences and the complexity of factors affecting alertness, beyond mere light exposure.

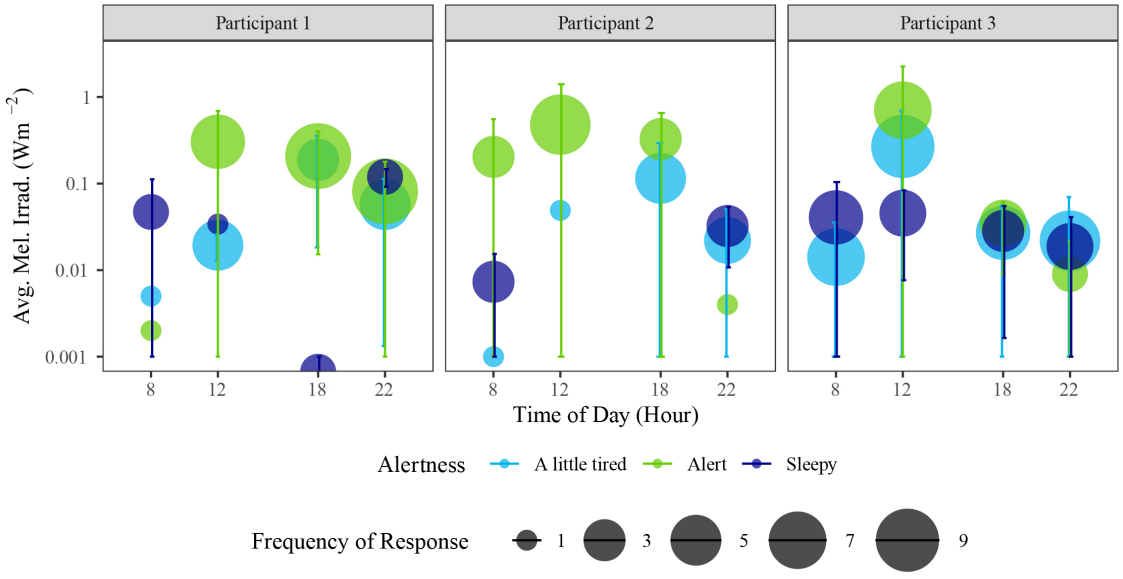

Figure 4: Participants' alertness levels by considering their light exposure and time of day.

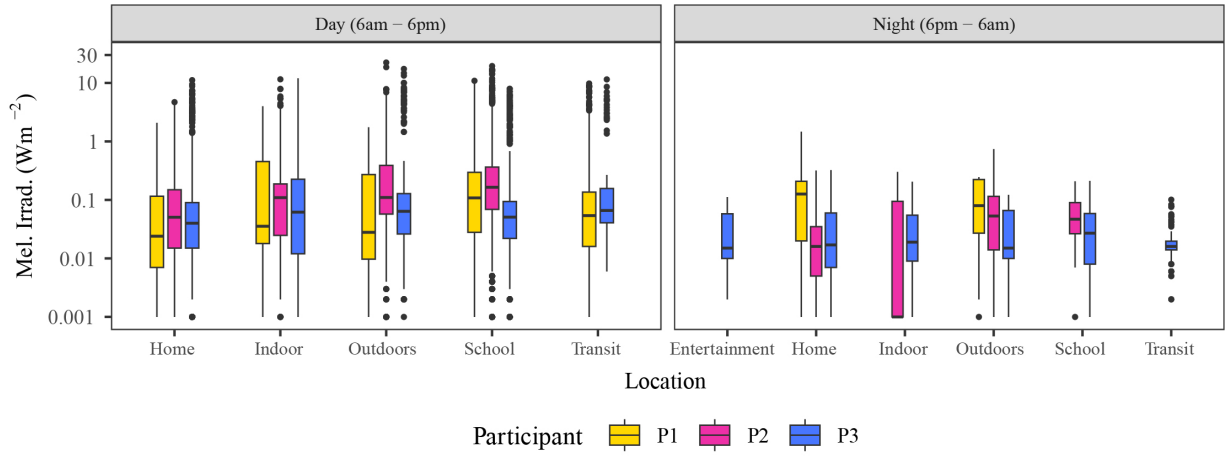

Figure 5: Participants' melanopic irradiance by location and time of day.

Schedule, time, and light exposure

Figure 5 analyzes the distribution of melanopic irradiance experienced by participants across various locations during day and night periods. During the daytime, from 6 am to 6 pm, the plot indicates a higher level of melanopic irradiance across all locations, which aligns with the expectation of increased light exposure due to the presence of natural daylight and electric light in working situations. In this example, during daylight hours, from 6 am to 6 pm, the data reveals some unexpected patterns. Participant 1 (P1) exhibits slightly higher median melanopic irradiance levels outdoors than at home. This could suggest that P1's home

environment has substantial daylight exposure. Alternatively, it might indicate that P1 spends significant time in well-lit areas of the home or uses lighting systems that emit high melanopic content during the day. In contrast, Participant 2 (P2) demonstrates more uniformity in melanopic irradiance levels across indoor environments, with a slight elevation at school. This pattern could be attributed to P2's daily activities, which might involve staying indoors in consistently lit areas or engaging in outdoor activities in places with limited direct sunlight. Participant 3 (P3), on the other hand, consistently experiences lower irradiance levels across all locations, implying limited exposure to bright light during the day, which could be due to lifestyle choices or the nature of the occupied spaces.

At night, which encompasses the hours from 6 pm to 6 am, there is an expected decrease in median melanopic irradiance across all locations. This reflects the reduced light exposure characteristics of nighttime conditions. The interquartile ranges are expected to be notably narrower during the night, indicating less variability in light exposure across different settings during these hours. These observations underscore not only the natural daylight pattern of light exposure but also the impact of artificial lighting in maintaining certain irradiance levels after dark.

Participant-specific data illustrates individual variability in light exposure. For example, the continued higher levels of irradiance in P1's home setting suggest an environment with persistent artificial lighting post-sunset, which could affect sleep patterns (Figure 6) and circadian rhythm, as excessive light at night can disrupt the natural circadian rhythm. The unexpected higher home irradiance levels for P1 and the lower overall exposure for P3 highlight the need for personalized considerations in lighting design and health recommendations. This analysis lays the groundwork for exploring how such exposure patterns might correlate with subjective wellbeing, alertness, and sleep quality.

Personal factors

Figure 6 shows the typical sleep durations for the three compared participants. Each horizontal bar represents the span of time during which each participant is typically asleep, marking from their mean bedtime to their mean waking time. We record specific daily sleep times as well, allowing analysis of the variance participants experience.

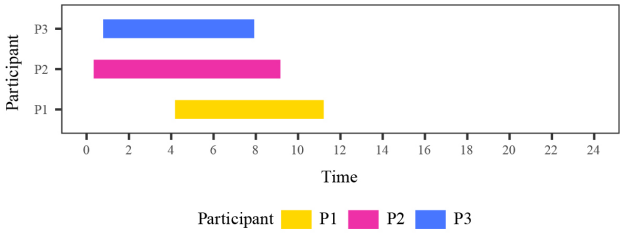

Figure 6: Participants' average sleep schedule.

The relationship between sleep patterns, light exposure, and alertness and wellbeing on an average or daily basis can therefore be assessed. Sleep schedules can potentially help explain variations in alertness reported in Figure 4. Participants might naturally report feeling more alert following their average wake-up times, as they have just ended their rest period. Conversely, as they approach their typical bedtimes, self-reported alertness could decrease. The length and quality of sleep might also play a role in the levels of alertness they experience during the day; for instance, a person with a longer, more consistent sleep pattern might exhibit higher alertness levels.

Although on a daily basis, sleep times and light exposure are recorded, the average sleep times plot (Figure 6) provides broad context for when participants are exposed to environmental light. For example, a participant with an early wake-up time (P2) would be exposed to morning light, potentially influencing their alertness and setting their circadian rhythm for the day. Such exposure to natural light in the morning has been linked to improved alertness and mood. In contrast, participants who wake up later (P1) may miss out on this exposure, which could have varying effects on their alertness levels.

Figure 7 provides a visual compilation of self-reported data from the three sample participants. The chart presents responses to a series of questions concerning their sleep quality, daily alertness, mood, and other wellbeing indicators, with each color palette representing a different response category. This chart offers insights into each participant's sleep quality and disturbances, with varying degrees of reported sleep anomalies. It also reveals the amount of time participants spend in well-lit areas and their reliance on artificial light, which could be linked to their reported productivity levels and pre-bedtime consumption habits, potentially influencing their sleep and alertness the following day.

Nap details and the number of awakenings are illustrated, providing a glimpse into the intricacies of each participant's sleep patterns. Morning alertness responses may correlate with these sleep characteristics, shedding light on how rest impacts their perceived state upon waking. Additionally, the participants' mood responses throughout the day could reflect an interplay between their sleep quality, environmental light exposure, and daily activities.

Daytime sleepiness levels are stacked against other responses, suggesting a connection between participants' sleep and their functioning during the day. These responses, when analyzed collectively, could allow for an assessment of how subjective sleep and wake experiences relate to one's exposure to light, their daily routines, and overall mood and wellbeing. This visual data representation correlates self-reported wellbeing and subjective measures of light exposure and activity patterns.

The interplay between sleep patterns, light exposure, and alertness is complex, as they are not only related within

individuals but also different between individuals. Participants' self-reported alertness, when contextualized with their sleep and light exposure patterns, suggests a rhythm to their daily experiences that extends beyond mere coincidence. This rhythm likely reflects the physiological impacts of light on human circadian rhythms, as well as the psychological and behavioural adaptations to individual lifestyles and environments.

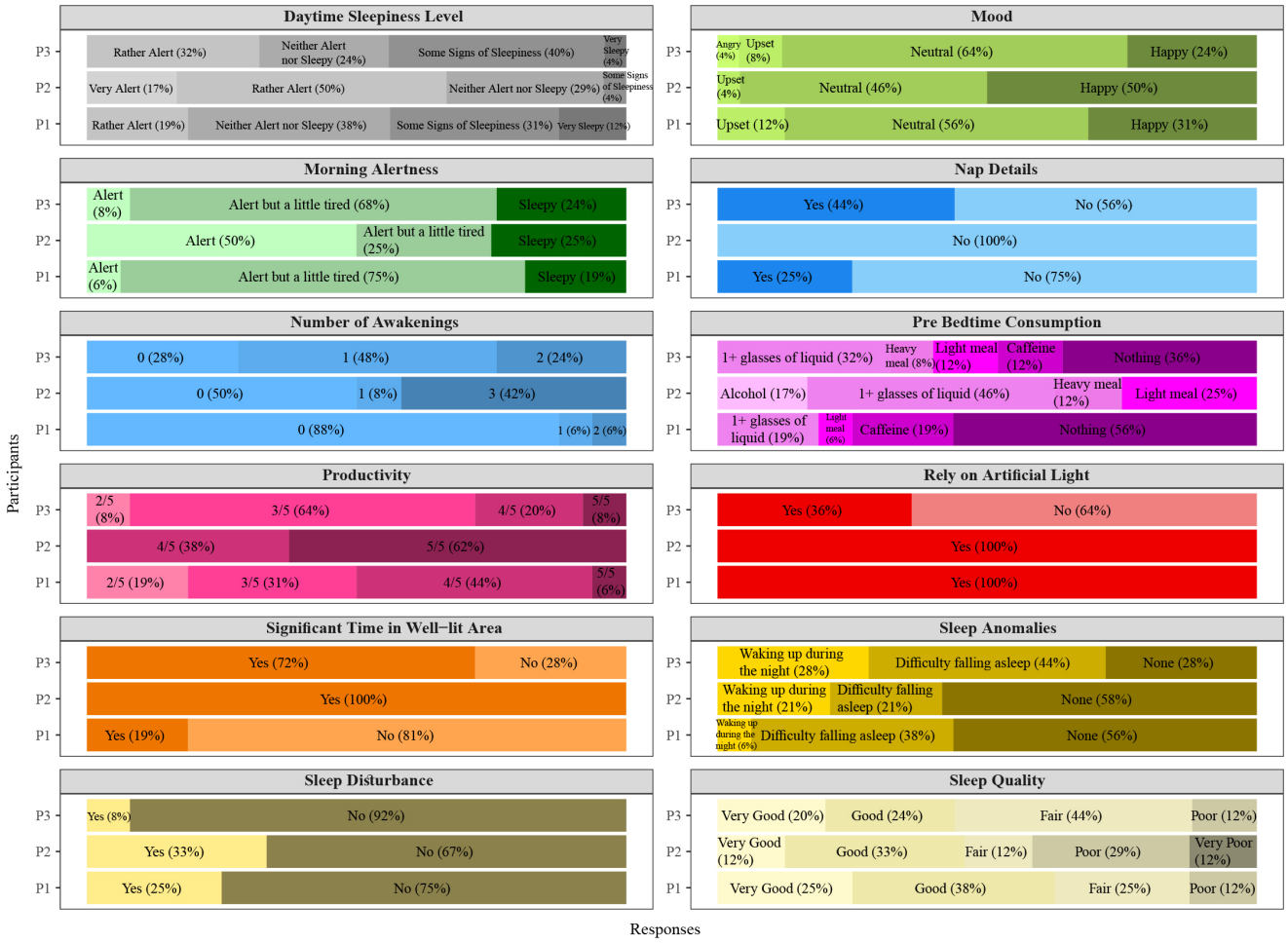

Figure 7: Participants' daily journal responses.

Discussion

This paper introduced a data collection methodology for evaluating the impact of light exposure on health and wellbeing through the use of data-logging sensors, smartwatches and daily journaling. The wearable technology employed offers dual advantages: continuous objective measurement of spectral irradiance and subjective assessment of personal wellbeing through smartwatch-facilitated surveys.

This methodology measures the multifaceted light interaction with individuals. Variability in light exposure and self-reported health and wellbeing indicators have highlighted the complex interplay of environmental factors and personal perceptions. The preliminary application of our methodology has revealed both expected and unexpected correlations, hinting at the role of light in circadian regulation and human wellbeing.

One of the challenges encountered includes ensuring participant compliance with the continuous wear of monitoring devices. There is also the consideration of the integrity of self-reported metrics, which are inherently subjective. This approach also sheds light on the participants' sleep quality, disturbances, and the potential influence of pre-bedtime routines on subsequent alertness and mood. Sleep data correlated with subjective wellbeing metrics might provide a richer understanding of how light exposure before bedtime can impact sleep patterns and the overall quality of rest. This underscores the individual differences in lifestyle and environmental interaction, which are essential considerations for future lighting strategies aimed at optimizing health outcomes.

Moving forward, this methodology could be essential in reevaluating light exposure standards, within various settings where individuals encounter different lighting conditions. By correlating detailed light exposure data

with self-reported health and wellbeing metrics, we pave the way for personalized lighting solutions. These tailored strategies hold the potential to align more closely with individual biological and psychological needs, thus promoting better overall health.

It is imperative for future applications of this methodology to consider the array of factors influencing alertness and wellbeing. The goal is to employ this methodology to hire participants for extended studies, thereby fortifying the empirical underpinnings of light exposure's role in wellbeing. Recognizing the physiological and behavioral adaptations will be crucial in designing interventions and lighting environments that support human health in a holistic manner. The proposed methodology serves as a template for subsequent explorations into the effects of light on human health. The insights from this study will inform the next steps in creating spaces that align with our biological needs, ultimately enhancing daily living and wellbeing.

Conclusion

This research demonstrates a comprehensive approach to understanding the intricate ways in which light exposure impacts human health and wellbeing. Through the innovative use of wearable spectral irradiance sensors and smartwatches, combined with detailed self-reporting daily journals, we investigate the complex relationship between light exposure and circadian rhythms, sleep patterns, mood, and alertness.

Our analysis highlights the significant impact of light on circadian regulation and overall wellbeing. Higher levels of melanopic irradiance were generally associated with increased alertness, particularly during morning hours, aligning with natural circadian preferences. However, variations in individual responses underscore the need for personalized lighting solutions to optimize health outcomes. The variability in light exposure and its effects on mood and alertness further demonstrates the intricate interplay between environmental light, individual behavior, and health.

Despite challenges in ensuring participant compliance and the inherent subjectivity of self-reported metrics, this study provides insights into the multifaceted effects of light on health. The methodology presented here can serve as a foundation for future research aiming to refine our understanding of these dynamics and guide the development of lighting standards and designs that better align with human biological and psychological needs.

This research highlights the critical need to account for individual differences and lifestyle factors in studying the health impacts of light exposure. As we continue to collect and analyze data from more participants, our aim is to build on these preliminary findings by including a broader, more diverse cohort. This expanded study will help us to uncover deeper insights into the relationships between light exposure, health, and wellbeing. By doing so, we aim to develop more adaptive and personalized lighting strategies that can improve daily living and enhance public health outcomes, steering the future of lighting design towards more human-centric solutions.

References

Amundadottir, M. L., Rockcastle, S., Sarey Khanie, M., & Andersen, M. (2017). A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior. *Building and Environment*, *113*, 5–21. https://doi.org/10.1016/j.buildenv.2016.09.033

Andersen, M., Mardaljevic, J., & Lockley, S. (2012). A framework for predicting the non-visual effects of daylight – Part I: Photobiology- based model. *Lighting Research & Technology*, *44*(1), 37–53. https://doi.org/10.1177/1477153511435961

Berson, D. M., Dunn, F. A., & Takao, M. (2002). Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock. *Science*, *295*(5557), 1070–1073. https://doi.org/10.1126/science.1067262

Brennan, M. T. (2018). *Outcome-based design for circadian lighting: An integrated approach to simulation & metrics*.

Danell, M., Ámundadóttir, M. L., & Rockcastle, S. (2020). Evaluating temporal and spatial light exposure profiles for typical building occupants. *Proceedings of the 11th Annual Symposium on Simulation for Architecture and Urban Design*.

Hammad, G., Wulff, K., Skene, D. J., Münch, M., & Spitschan, M. (2024). Open-Source Python Module for the Analysis of Personalized Light Exposure Data from Wearable Light Loggers and Dosimeters. *LEUKOS*, 1–10. https://doi.org/10.1080/15502724.2023.2296863

Hattar, S., Liao, H.-W., Takao, M., Berson, D. M., & Yau, K.-W. (2002). Melanopsin-Containing Retinal Ganglion Cells: Architecture, Projections, and Intrinsic Photosensitivity. *Science*, *295*(5557), 1065–1070. https://doi.org/10.1126/science.1069609

Inanici, M., Brennan, M. T., & Clark, E. (2015). Spectral lighting simulations: Computing circadian light. *Building Simulation Conference Proceedings*, 1245–1252.

International Commission on Illumination (CIE), & Schlangen, L. J. M. (2018). *International standard: CIE system for metrology of optical radiation for iPRGC-Influenced responses to light*. CIE. https://doi.org/10.25039/S026.2018

Jakubiec, J. A., & Alight, A. (2021, September 1). *Spectral and biological simulation methods for the design of healthy circadian lighting*. 2021 Building Simulation Conference. https://doi.org/10.26868/25222708.2021.30535

Jayathissa, P., Quintana, M., Sood, T., Nazarian, N., & Miller, C. (2019). Is your clock-face cozie? A smartwatch methodology for the in-situ collection of occupant comfort data. *Journal of Physics: Conference Series*, *1343*(1), 012145. https://doi.org/10.1088/1742-6596/1343/1/012145

Kim, J., Bauman, F., Raftery, P., Arens, E., Zhang, H., Fierro, G., Andersen, M., & Culler, D. (2018). Occupant comfort and behavior: High-resolution data from a 6-month field study of personal comfort systems with 37 real office workers. *Building and Environment*, *148*. https://doi.org/10.1016/j.buildenv.2018.11.012

Konis, K. (2019). A circadian design assist tool to evaluate daylight access in buildings for human biological lighting needs. *Solar Energy*, *191*, 449–458. https://doi.org/10.1016/j.solener.2019.09.020

Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., Figueiro, M. G., Gamlin, P. D., Lockley, S. W., O'Hagan, J. B., Price, L. L. A., Provencio, I., Skene, D. J., & Brainard, G. C. (2014). Measuring and using light in the melanopsin age. *Trends in Neurosciences*, *37*(1), 1–9. https://doi.org/10.1016/j.tins.2013.10.004

Mardaljevic, J., Andersen, M., Roy, N., & Christoffersen, J. (2014). A framework for predicting the non-visual effects of daylight – Part II: The simulation model. *Lighting Research & Technology*, *46*(4), 388–406. https://doi.org/10.1177/1477153513491873

Maskarenj, M., Deroisy, B., & Altomonte, S. (2022). A new tool and workflow for the simulation of the non-image forming effects of light. *Energy and Buildings*, *262*, 112012. https://doi.org/10.1016/j.enbuild.2022.112012

Nixon, A., Robillard, R., Leveille, C., Douglass, A. B., Porteous, M., & Veitch, J. A. (2024). 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

Pierson, C., Aarts, M. P. J., & Andersen, M. (2022). Validation of spectral simulation tools in the context of ipRGC-influenced light responses of building occupants. *Journal of Building Performance Simulation*, 1–19. https://doi.org/10.1080/19401493.2022.2125582

Postnova, S., Lockley, S. W., & Robinson, P. A. (2018). Prediction of Cognitive Performance and Subjective Sleepiness Using a Model of Arousal Dynamics. *Journal of Biological Rhythms*, *33*(2), 203–218. https://doi.org/10.1177/0748730418758454

Provencio, I., Jiang, G., Grip, W. J. D., Hayes, W. P., & Mark D. Rollag. (1998). Melanopsin: An opsin in melanophores, brain, and eye. *Proceedings of the National Academy of Sciences*, *95*(1), 340–345. https://doi.org/10.1073/pnas.95.1.340

Webler, F. S., Chinazzo, G., & Andersen, M. (2021). Towards a wearable sensor for spectrally-resolved personal light monitoring. *Journal of Physics: Conference Series*, *2042*(1), 012120. https://doi.org/10.1088/1742-6596/2042/1/012120

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

Zeitzer, J. M., Dijk, D., Kronauer, R. E., Brown, E. N., & Czeisler, C. A. (2000). Sensitivity of the human circadian pacemaker to nocturnal light: Melatonin phase resetting and suppression. *The Journal of Physiology*, *526*(3), 695–702. https://doi.org/10.1111/j.1469-7793.2000.00695.x