Evaluating the Circadian-Effectiveness of Light through Personal Light Exposure Measurement: An Initial Test Using a Low-Cost and Wearable Spectrometer in Home-Office

Armin Amirazar[1], Mona Azarbayjani[1], Maziyar Molavi[2]

[1]University of North Carolina at Charlotte, Charlotte, NC
[2]Raja University, Qazvin

ABSTRACT: Lack of affordable and reliable wearable spectrometers to record the characteristics of light exposure as a stimulus that affects the human circadian system is evident. This study aimed to measure and evaluate the circadian effectiveness of personal lighting conditions of two office workers using a low-cost and wearable spectrometer. We continuously measured personal lighting conditions of two office workers over the course of eight days. They also were asked to self-report their daily schedules and locations during the measurements. Comparison between two office workers across the study period revealed significant benefits of utilizing dynamic electric lighting in combination with daylight regarding circadian-effective light level that they were exposed to. However, outcomes were dependent on inter-individual differences such as different wake/sleep patterns, and workspace characteristics such as distance to window. The present study is the first to employ a low-cost and wearable spectrometer that allows to measure light source's SPDs in real-time and store personal light exposure data on Firebase cloud database using wireless communication. The spectrometer prototype developed in this study has potential to be integrated into an IoT-based smart lighting system for continuous monitoring of personal lighting conditions.

KEYWORDS: Circadian-effectiveness of light; Non-visual effects of light; Circadian Stimulus; Low-cost spectrometer; Personal lighting condition

INTRODUCTION

Natural light is an important element of building design that influences human health, comfort, performance, and well-being. Natural light provides a combination of the right types of light with the right spectral content at the right times. Humans' daily rhythms in behavior and physiology such as wake/sleep patterns have evolved under natural light–dark cycles over millions of years. However, the invention of electric lighting has dramatically changed human home, social and work environments by shifting the light exposure pattern from natural light to electric light over the past decades. Currently, in the US, exposure to natural light is significantly reduced as people spend more than 87% of their working hours indoors in comparison to the 1800s where they spent about 90% of their time working outside (Klepeis et al. 2001). Despite the advantages of this invention for humankind, lack of natural light exposure during the day and increased exposure to electric light during the night is associated with psychological, physical, and mental health issues that can disrupt circadian rhythms and sleep. Circadian rhythm is a natural process that regulates sleep-wake cycle by synching the internal clock to roughly a 24-hours diurnal cycle in an outdoor environment. Disruption of circadian rhythm may result in mood disorders, displacement of wake/sleep cycle, melatonin suppression, and phase-shifting of the circadian system. Ocular light exposure provides measurable benefits for both visual and non-visual systems. Even though we interact with our environment through a visual system, the discovery of the third class of photoreceptor within the eye (Berson, Dunn, and Takao 2002), named Intrinsically Photoreceptive Retinal Ganglion Cells (ipRGCs), placed increased attention on unseen effects of light that influence our mood, alertness, emotion, health and sense of well-being. Deviation from regular light-dark exposure patterns negatively affects sleep (M. G. Figueiro and Rea 2010), mood (M. G. Figueiro et al. 2017), performance (Mallis and DeRoshia 2005), and is associated with a range of health issues such as seasonal affective disorder (Thorne et al. 2009), and even cancer (Cordina-Duverger et al. 2018). Nowadays, as we spend a large proportion of our time in the built environment, we are exposed to less light during daytime hours and more light during nighttime hours than what we would have naturally received across day and night (Knoop et al. 2019). For the past seven decades, the exposure to electric light has increased between 3% and 6% annually as people are mostly indoors that consequently may increase the likelihood of disrupting the circadian rhythms (Kyba et al. 2017). In recent years, the work landscape has changed dramatically, as companies have started to cut costs by downsizing their office spaces and allowing their employees to work-from-home (WFH). The number of people remotely WFH surged by 173% from 2005 to 2018 (Messenger 2019). The pace of this change is increasing as a direct result of the COVID-19 pandemic, as currently, an ever-increasing number of people are WFH. Studies show strong links between an irregular natural day-night cycle and disruption of circadian rhythms, poorer sleep quality, impairment of cognitive function, and the onset of depression in office workers without or with less access to natural light (Mariana G Figueiro 2017). Therefore, it has never been more important to capture evidence from human interactions within existing buildings and investigate the impacts of indoor lighting conditions on human health, comfort, and wellbeing. Currently, there is a lack of consensus on circadian lighting metrics and/or the exact threshold to support circadian-effectiveness of lighting in working environments. Some standards in the field of light and lighting such as, WELL Building Standard v2 (SEMINAR 2020), have recently begun to include metrics that address the proper light exposure for supporting biological health and adjusting the circadian rhythm with a natural day-night cycle. The WELL standard recommends using the two most popular circadian lighting metrics for measuring light exposure: Equivalent Melanopic Lux (EML) and Circadian Stimulus (CS). The effect of light exposure on the circadian system should be calculated by taking into account the output of all three types of retinal photoreceptors, rods, cones, and ipRGCs, in the human eye (Hattar et al. 2003). CS not only considers both spectrum and intensity of light source, but also it ties to all three types of retinal photoreceptors which is necessary for assessing circadian lighting (M. Rea and Figueiro 2018). However, EML ties to a single photoreceptor and ignores any impacts of the rods and cones. In this study, we used CS to measure the circadian-effectiveness of light using the collected data from the wearable spectrometer. Tailoring indoor lighting conditions in accordance with individuals' specific needs and desires can promote health and wellbeing in the built environments. Previous studies suggested we consider at least six factors (timing, duration, history, intensity, spectrum, and directionality of light exposure) when assessing the effects of light beyond vision (Juliëtte van Duijnhoven, Aarts, and Kort 2020). The spectrum and intensity of the light exposure need to be aligned with the human circadian system throughout the day to avoid circadian disruption and enhance human health and productivity. For example, exposure to light in the early morning advances the timing of the circadian clock; however, receiving bright light during the evening delays the timing of the biological clock and may cause circadian disruption which consequently reduce sleepiness (Ruger et al. 2006). Thus, people who spend a large proportion of the day under electric light, expose themselves to steady light intensities and spectrum, specifically during the evening/night hours, which may shift the human biological clock (Münch and Bromundt 2012). In the field of architecture and lighting design, different metrics, techniques, and devices need to be utilized other than what traditionally have been used by lighting designers to address human's biological needs for light. In this way, wearable technologies can be used to measure personal light conditions continuously in its most comprehensive forms (Spectral Power Distribution of light), which is essential for the lighting community. Recently, the term "personal lighting conditions" was commonly used when measuring lighting conditions continuously at the individual level (Juliëtte van Duijnhoven, Aarts, and Kort 2020). The inclusion of this term is recommended, particularly in studies that investigate the non-visual effects of light on humans (J van Duijnhoven et al. 2018). The objective of the present study was to measure personal lighting conditions of two-office workers continuously over the course of eight days in a home-office using a recently developed wearable spectrometer. We used CS to evaluate the circadian effectiveness of various lighting conditions during the study period. We further explore the effect of work schedules in response to light exposure between two office workers.

1.0 METHOD

We conducted a field study using a novel wearable spectrometer to measure participants' light exposures continuously in a home-office over a period of eight days in Seattle, WA. In the following sections, the process of collecting and analyzing the data, and the instrument used for the purpose of data collection are described in detail.

1.1. Test space selection criteria and participants

Data collection was performed at a home-office, which is on the third floor of a residential building located at Seattle, WA. Fig 1 shows the schematic plan of the home-office and its surrounding urban context. The home-office has five separate spaces including a working space, a kitchen, a bathroom, a living room furnished with a TV for resting time, and a bedroom for sleep at night. The working space had one West-side window that was covered with a venetian blind. Except for the distance to the window, we attempted to minimize the variation between the features in participants' working spaces. Features are similar for both participants included: room size; wall and furnishing color; siting orientation; amount and placement of furniture and luminaire; size, building orientation, and blind condition of the window(as well assize, number, and the height of the monitors). The living room had a west-facing window with a fully closed blind during the period of this study and there was a small source of lighting coming from a TV that can be ignored. The bedroom had an east-facing window that was covered during the nighttime by a fully closed blind, because this space was only used for sleep. We chose Seattle as it is the cloudiest major US city in the lower 48 states (Walker 2010). On average, Seattle has 226 days (62% of days) with clouds covering more than three-quarter of the sky and 308 days (84% of days) with clouds covering over one-quarter of the sky in a year. Thus, with less sunny days, there is limited access to daylight as an ideal source of light for the human circadian system. The length of the day varied significantly in Seattle over the course of the year. The present study was conducted between September 27 and August 4 when sunrise was at about 07:00 and sunset was at around 19:00 with a total daylight of less than 12 hours .Two office workers (one male: age 36 years and one female: age 36 years) volunteered for the study.

1.2. Lighting Interventions

We built a custom luminary for the study using one ilumi BR30 Bluetooth LED Smart bulb ("Ilumi" Retrieved February 20, 2021) that was inserted into a luminaire head on the ceiling of the working space to be only used during Day 7 and Day 8 of the study. A warm LED (2700 K) was used between Day 1 and Day 6 that was replaced with a new ilumi BR30 Bluetooth LED Smart bulb. The color temperature of this multicolor light source is adjustable from 2700 K to 6500 K, at nearly any brightness level. The ilumi app was used to automatically turn the light source on at 7 AM and turn it off at 11 PM between Day 7 and Day 8. To improve the daily routine, an additional layer of control , which is called "Circadian Experience" was used to schedule lighting brightness and color setting depending on the time of day in accordance with human circadian rhythm. The lighting automatically transitioned gradually from cool energetic white (6500 K) in the morning to a relaxing warm (2700 K) in the evening. The Circadian Experience was utilized to replicate the natural light cycle. The luminaire was placed in the middle of the working space to have the equal effect on both participants.

1.3. Data Collection and Protocol

A wearable spectrometer was used to collect Spectral Power Distributions (SPD) every 30 seconds from the participants. The process of calibration and the accuracy of the device can be found in a prior publication (Amirazar et al. 2021). We provided the required materials and instructions to participants prior to commencement of the study. We asked participants to wear the wearable spectrometer as a pendant (at chest height) for eight consecutive days during data collection periods. The device attached to the participants' clothes at the left-hand side of the chest and measured light exposure at the similar view direction of the eye in the vertical plane. We asked participants to keep the wearable spectrometer always uncovered. Each participant wore a device during waking hours and placed the device next to their bed at the charging station during sleep. Participants had different working schedules as one started working at 7 AM (± 30 minutes) and the other one from 11 AM (± 30 minutes), but they went to bed at the same time (11 pm).

a) b)

Figure 1: Example of home-office layout. a) plan shows where the subjects were seated, positions of computer monitors, LED smart bulb, and locations and view orientations of HDRI sensors, b) surrounding urban context.

To compare light-dark patterns between the two participants, we asked participants to keep a log of their bedtimes, waketimes (waking hours), and working times (when they are behind the desk) during the data collection period. To evaluate the circadian efficacy of different indoor lighting conditions, we designed different lighting conditions for each day of the data collection period (see Fig. 2). Fig 2 shows the protocol designed for the present study. The study was performed over eight days. From Day 1 to Day 5, the participants had freedom to close the blind if they experience excessive direct sunlight entering from the window or open it if they need more daylight in the working area. Additionally, the participants had freedom to turn on/off a warm LED (2700 K) placed in the middle of room. During day 6, the blind was fully retracted, and electric light was kept off to record the lighting conditions in the working space entering from the West-facing window. During day 7, we turned on the ilumi BR30 Bluetooth LED Smart bulb in the working space and closed the blind to investigate the effects of lighting intervention. Finally, during day 8, the blind was fully retracted, and ilumi BR30 Bluetooth LED Smart bulb was turned on to allow for both natural light and electric light in the working space.

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
Wearable device	Wear	Wear	Wear	Wear	Wear	Wear	Wear	Wear
Lighting Intervention	Off	Off	Off	Off	Off	Off	On	On
Blind	Adoptable	Adoptable	Adoptable	Adoptable	Adoptable	Fully retracted	Fully closed	Fully retracted

Figure 2: The eight-day protocol for the study.

1.4. Analysis of measured SPD data

We employed a mathematical model of human circadian phototransduction proposed by Rea et al. to calculate Circadian Light (CL_A) and Circadian Stimulus (CS) for any spectral irradiance distribution (M.S. Rea et al. 2005; M.S. Rea et al. 2012). The CL_A metric is weighted irradiance of light incident at the cornea to reflect the spectral sensitivity of the human circadian system. Additionally, the CS metric is determined by how much melatonin is suppressed by nocturnal lighting after one-hour light exposure from threshold (CS = 0.1) to saturation (CS = 0.7) to reflect the absolute sensitivity of the circadian system (M.S. Rea et al. 2010). We used MATLAB to analyze each SPD collected from the wearable spectrometer to calculate circadian light (CL) and circadian stimulus (CS). First, we converted the corneal SPD into CL_A, and then, second, CL_A is transformed into CS. CS metric was employed to quantify the effectiveness of corneal spectral power distribution in order to stimulate the human circadian system. It should be noted that a new light measurement strategy is currently recommended to report corneal spectral irradiance in five illuminance quantities by calculating the effective irradiance for rhodopic, melanopic, cyanopic, chloropic and erythropic independently (CIE 2018). However, currently, there is a lack of biological lighting metrics that utilize these five illuminance quantities for the purpose of assessing the lighting conditions in indoor environments. Therefore, we reported the results in units of CS, as the WELL Building Standard recently recommended this unit of analysis (SEMINAR 2020). We analyzed the data collected from the wearable spectrometer to compare the total light exposure among all eight days for both participants. As we only altered the lighting conditions in the working space, we analyzed the collected data based on the time participants spent in this space (working hours) to better understand the circadian effectiveness of different lighting conditions. Moreover, we analyzed the data from the wearable spectrometer to assess the total light exposure during both working hours and the total light exposure during waking hours for each participant. We calculated the total light exposure during both working hours and waking hours based on the times participants reported being at the working space and being awake, respectively. Additionally, we went one step further to analyze the light exposure on hourly basis during both working hours and waking hours and for different parts of a day, which included Morning (0600-1200), Afternoon (1200 - 1700), Evening (1700 - 2000), and Night (2000 - 0600). This helped us to better understand the circadian stimulus potential of light for each participant during his/her waking and working hours within different hours and different parts of the day. It is important to note that each participant has a different schedule, so the working hours and waking hours of each participant differ from that of the other.

1.5. Statistical Analysis

Statistical analysis was performed with SPSS Version 27. statistical software package (IBM, Armonk, NY, USA). A one-way ANOVA was conducted on light exposure data with the factors 'days' (eight days: day 1, day 2, day 3, day 4, day 5, day 6, day 7, and day 8) to determine effects of the light intervention across the eight-days study period. Tukey's post hoc analysis was further applied to compare the significant main effects and interactions of attributes where significant differences were found in ANOVA. A two-way ANOVA was conducted to explore how the participant's schedule (3 states: sleep, waking, and working) and daytime periods (4 parts: 6 a.m-12 p.m. = morning, 12 p.m-5 p.m. = afternoon, 5 p.m-8 p.m. = evening, and 8 p.m-6 a.m. = night) affect light exposure (CS) over the period of the study. Results were considered to be statistically significant when $p < 0.05$.

2.0 RESULTS

2.1. Monitoring the variations of outdoor lighting conditions

As shown in Fig 3, we monitored the outdoor lighting conditions by utilizing two low-cost and programmable High Dynamic Range Image (HDRI) sensors consisting of Raspberry Pi microcomputers with a 5-megapixel fisheye lens with a 180-degree field of view (FOV) to provide the visual record of interior and exterior scenes at the working space. We applied a false color luminance mapping on each HDR to visualize the luminance distribution of the window-facing view and exterior scene and to monitor any variations of outdoor lighting conditions during the study period from 08:00 to 19:00 between September 27 and August 4. Comparison between Day 1 and Day 8 of exterior scenes (Fig 3b) shows outdoor lighting conditions were almost the same among all eight days with a clear sky with no cloud cover. For the window-facing view of the interior scenes, Fig. 3a shows a significant decrease in window light exposures during Day 7 compared to Days 7 and 8, as the blind was fully closed for the entire day. Closer inspection of Fig. 3a shows that the participants closed the blind mostly during afternoon between Day 1 and Day 5 to reduce the excessive sunlight entering from the window. During Day 6 and Day 8, the blind was fully retracted for the entire day.

2.2. Exploring the circadian effectiveness of various lighting conditions

Circadian stimulus (CS) was estimated by analyzing SPD collected from the wearable spectrometer worn by the participants. Figs. 4-6 summarize the outcomes in terms of the mean CS level over the eight-days study period grouped into the entire day, working and waking hours, and daytime periods. As expected, the one-way ANOVA revealed significant differences in CS values for the study days, $F(7, 43261)=163.665$, $p<0.001$. *Post-hoc* analysis using the Tukey HSD model show significant ($p<0.001$) difference in mean CS levels between two intervention days (Day 7 (M = 0.12, SD = 0.19), and Day 8 (M = 0.14, SD = 0.21)) and the first six days. Fig. 4 shows two intervention days (Day 7 and Day 8) had the highest CS value compared with other study days. As shown in Fig. 5 the mean CS level dramatically increased from Day 6 to Day 8 during both waking hours and working hours. For different daytime periods, there is a surge in mean CS level from Day 6 to Day 8 during morning and evening, except for afternoon as there was a slight decrease from CS = 0.31 to CS = 0.3 between Day 7 and Day 8, respectively (Fig. 6).

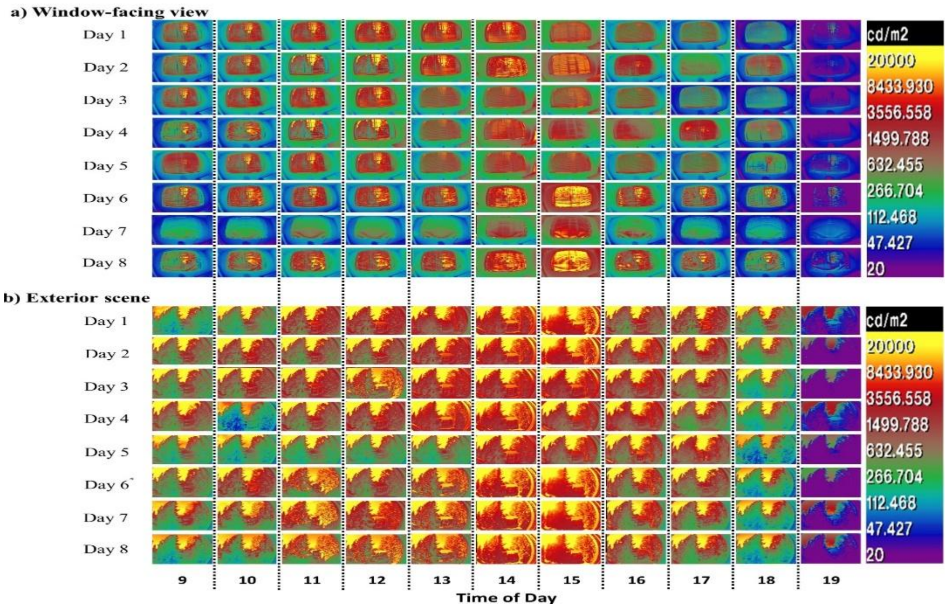

Figure 3: False Color luminance mapping of a) window-facing views and b) exterior scenes from 09:00 to 19:00 between Day 1 and Day 8.

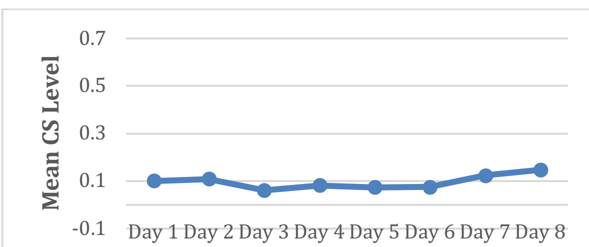

Figure 4: Mean CS values measured for an ***entire day*** for each study day. The error bars represent the standard error of the mean

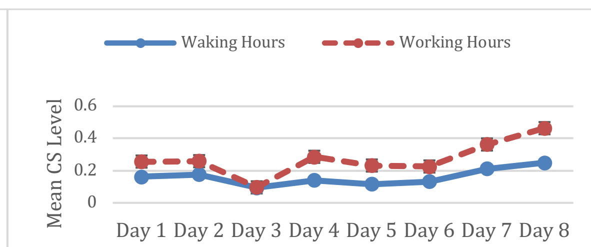

Figure 5: Mean CS values measured during ***working hours and waking hours*** for each study day. The error bars represent the standard error of the mean

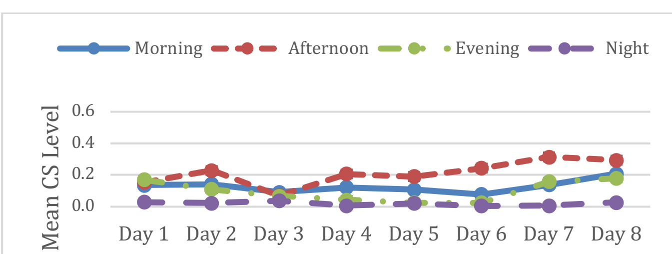

Figure 6: Mean CS values measured during ***different daytime periods*** for each study day. The error bars represent the standard error of the mean

2.3. Exploring personal lighting conditions per individual

Fig. 7 presents daily schedule of both office workers for all eight-day study period. Each participant self-reported his/her daily schedules and locations during the entire study period. Participants had different sleep-wake schedules (blue and grey cubes) and working schedules (orange cubes) during the study. As shown in Fig. 8, the average reported duration of working hours were 345 minutes (SD = 140) and 315 minutes (SD = 138) for participant 1 and participant 2, respectively. The sleep-wake schedule of each participant was different from one another. The average reported duration of waking hours were 960 minutes (SD = 30) and 720 minutes (SD = 50) for participant 1 and participant 2, respectively. In general, participant 2 had longer sleep duration by approximately 12 hours compared with 8 hours for participant 1. It should be noted that participant 2 was not presented in the working area during Day 3. Figs. 8-11 can be used to understand the significant impact of individual differences between participants on measured light exposure data reported in units of CS. Figs. 8–10 compared the measured levels of CS between two participants during each study day, waking hours, and only working hours over the duration of the study. The two-way ANOVA revealed significant main effects of the participant's schedule, $F(2, 43130)=4697.851$, $p<0.001$. The mean CS level increased from Day 6 to Day 8 for both participants. Fig. 10 shows mean CS values was significantly higher for participant 2 during all study period (CS > 0.3), except Day 3, compared with participant 1. Fig. 11 presents the mean CS level for four different daytime periods acquired by taking light exposure data of each participant over the duration of the study. There was a significant main effect of daytime periods, $F(3, 43130)=203.431$, $p<0.001$. For participant 2, mean CS level increased between morning and afternoon, followed by a decrease towards the night during all eight-study days, except an unexpected surge on mean CS level during evening on Day 7. For participant 1, mean CS level decreased from morning to night during all three-study days, expect a slight increase between afternoon and evening on Day 1 and Day 8 and a unexpected increase from morning to afternoon on Day 5.

a) Participant 1 **b) Participant 2**

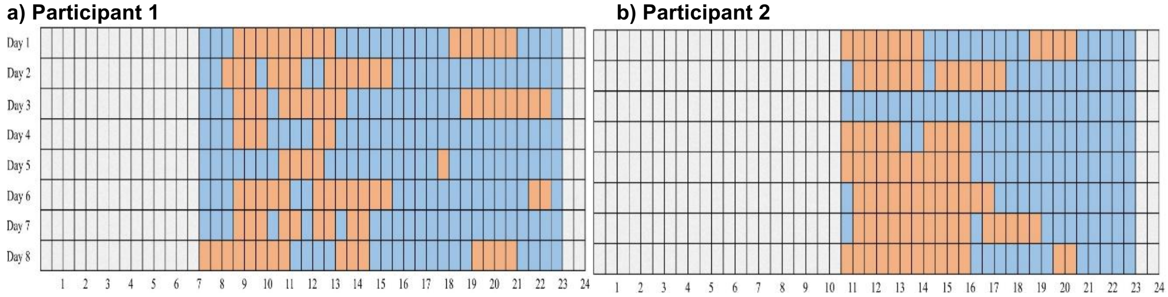

Figure 7: Participant profiles and their daily schedule and locations for all eight-day study period. Orange, blue, and grey cubes indicate the hours when each participant was working, waking, and sleeping, respectively.

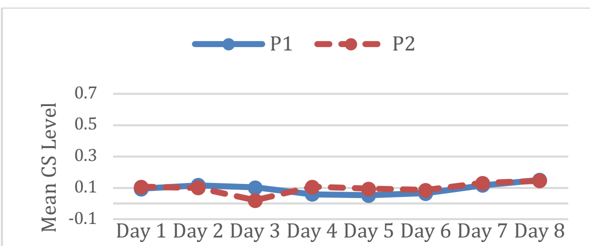

Figure 8: Mean CS values measured at the chest of each participant for an entire day. The error bars represent the standard error of the mean.

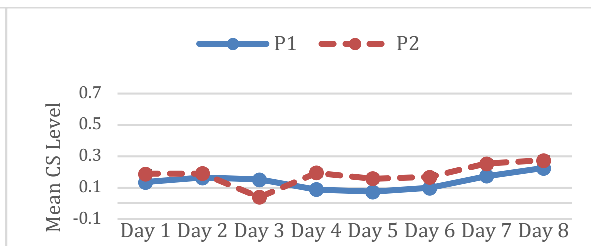

Figure 9: Mean CS values measured at the chest of each participant during **waking** hours. The error bars represent the standard error of the mean

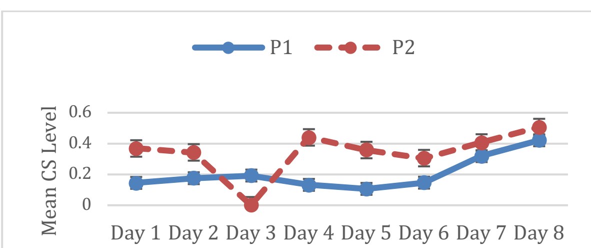

Figure 10: Mean CS values measured at the chest of each participant during only **working** hours. The error bars represent the standard error of the mean.

DISCUSSION AND CONCLUSIONS

This research assessed the practical applicability of an affordable and wearable spectrometer in the context of aiding individuals to have healthier living with relation to light. In this study, the circadian-effectiveness of light was measured in terms of CS across the eight-day study period. Previous studies showed that the office workers who received CS ≤ 0.15 in the morning had difficulty sleeping at night with higher levels of depression compared to those who received CS ≥ 0.3 in the morning (M. G. Figueiro et al. 2019; M. G. Figueiro et al. 2017). Hence, in the present study, CS≥ 0.3 is considered as a high circadian-effective light level that reduces sleepiness and improves energy and alertness in office workers. It should be noted that on each day of the study, the same wearable spectrometer was used by each participant. We evaluated the circadian effectiveness of lighting during a two-day intervention (Day 7 and Day 8) following the baseline between Day 1 and Day 6 for two office workers. The findings show a significant difference between the first six days and, Days 7 and 8 in terms of CS value that indicated the potential of utilizing dynamic electric lighting in combination with daylight to have a significant impact on circadian stimulus potential of indoor lighting. As expected, participants were exposed to higher amounts of circadian-effective light during working hours compared to waking hours (Fig. 5). CS values during waking hours for the two intervention days were above 0.2 (see Fig. 5). We found that the two office workers received high circadian-effective light level (CS ≥ 0.3) while at work (during working hours) on intervention Day 7 and Day 8 compared to baseline days (Fig. 5). The average CS value for both participants was 0.37 on Day 7, followed by a considerable increase to 0.45 on Day 8. Increasing circadian stimulation during Day 8 was because of access to a mixture of daylight and electric light compared to Day 7 where electric light was the only source of lighting.

a) Participant 1 **b) Participant 2**

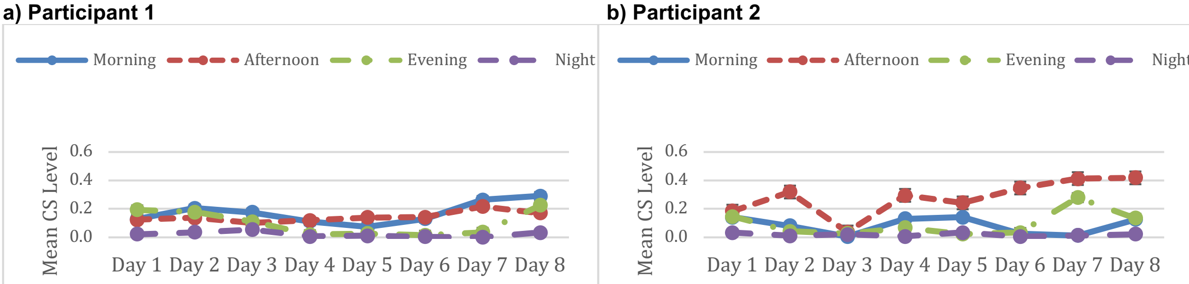

Figure 11: Mean CS values measured at the chest during different daytime periods for a) participant 1, and b) participant 2. The error bars represent the standard error of the mean

The importance of daylight and its impact on improving the level of circadian-effective light in indoor spaces is comparable to the studies presented by (Konis 2018) and (Boubekri et al. 2014) who showed the benefits of daylit spaces in comparison with windowless environments in regard to increasing circadian stimulation. Participants were exposed to a significantly higher amount of circadian-effective light in the afternoon for most of study days compared to other daytime periods (Fig. 6). The fact that the mean CS value increases during the afternoon can be explained by the larger proportion of time that both participants spent at their working space with higher circadian-effective light levels compared to other spaces such as the living room and bedroom (see Fig. 7). Even though we performed this study in summer 2020 and we only have two participants doing the same job tasks in the same location, we still found large individual differences between two participants in their personal lighting conditions. These differences between the personal lighting conditions of two participants may be explained by mixed physiological/behavioral differences and workspace characteristics such as different wake/sleep patterns, work schedules and distance to window. As mentioned in section 2.1, the variation between workspace characteristics were minimized for both participants. Variations as siting orientation, amount and placement of furniture and luminaire, size of the building, building orientation, blinds and condition of window coverings, as well as the size, number, and the height of the monitors were similar for both participants. Despite the fact that the study was performed on sunny days during the summer season, both office workers were generally being exposed to low circadian-effective light level (CS ≤ 0.3) during waking hours (Fig. 9). We can speculate on a few reasons why the measured amount of circadian light for both participants for the entire day (Fig. 4) and during waking hours (Fig. 5) on all eight study days was low. One is due to the building design, a narrow facade and a small window-to-wall ratio that had been poorly designed to provide enough daylight availability in the space (Fig. 1). Another is due to the building orientation, as the West-facing window had only about two hours of direct sunlight (Fig. 3), while the East-facing window did not provide enough daylight availability for even the bedroom during the daytime period. The third reason would be due to the lack of enough number, placement, intensity, and spectrum of electric lighting that were installed in the building where less daylight is available. As expected, distance from the West-side window at the working space was found to be associated with a difference in participants' lighting conditions. Except for Day 3, the average CS values during working hours for participant 2 was above 0.3 (Fig. 10). In contrast, for participant 1, the average CS values during working hours was above 0.3 only on two intervention days (Day 7 and Day 8). As shown in Fig. 10, a 2 meter increasing distance to the West-facing window resulted in a significant increase in the mean CS level between Day 6 and Day 8 when daylight was the source of light for the working space. The fact that the CS level reduces for an increasing distance can be explained by the limited penetration depths of daylight in a room (Iversen et al. 2013). These results are consistent with previous studies showing distance-to-window has a significant impact on the personal lighting conditions (Juliëtte van Duijnhoven et al. 2020), particularly the amount of circadian-effective light that participants were exposed to during daytime (M. G. Figueiro and Rea 2016). These findings highlight the importance of considering the impact of distance to window when measuring the personal lighting conditions within daylit spaces. The difference in personal lighting conditions between two participants was also found and can be impacted by changing the sleep-wake schedule and working schedule of the office workers. As already mentioned in section 2.6, the working hours and waking hours were calculated in terms of the amount of time each participant spent at the working space and being awake, respectively. Although participant 2 woke up about 4 hours later than participant 1, the percentage of time spent at the working space was much higher compared to participant 1 (Fig. 7). Participant 2 received a higher amount of circadian-effective light in the afternoon compared to other daytime periods during all eight-day study periods, except Day 3 when participant 2 was not presented in working area for entire day (Fig. 11). However, participant 1 was exposed to the highest level of circadian-effective light in the morning for intervention Day 7, and Day8. Additionally, a low CS level on Day 4 and Day 5 compared with other study days for participant 1 can be explained by the lower number of working hours during these days (see Fig. 7). Similarly, for participant 2, a considerable decrease in CS level on Day 3 was the results of significant decrease in the number of working. Future research is recommended to include the larger number of participants with different age groups, different jobs, different culture, and different genders to explore a more complete set of factors to better understand the actual lighting conditions at the individual level. The present study is the first to employ a low-cost and wearable spectrometer that allows us to measure light source's SPDs and store the collected data on the Firebase cloud database using wireless communication. The concept of a 'personalized smart lighting system' can be deployed by continuously monitoring personal lighting conditions in real-time using the developed spectrometer and controlling these lighting conditions by utilizing an IoT-based smart lighting system.

3.1. Limitations of the study and

First, due to the impact of COVID pandemic, we had a limited number of participants in this study. The small sample size does not allow us to investigate the inter-individual differences in response to light exposure between larger populations with different ages, genders, and jobs. Physiological, genetic, behavioral, and cultural differences between individuals may cause different biological responses even under the same lighting conditions.

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