RESULTS REPORT:

MEASURING PERSONAL LIGHT EXPOSURES, HEALTH, AND WELLBEING OUTCOMES

FEDERAL CENTER SOUTH

SEATTLE, WASHINGTON

Submitted to:

U.S. General Services Administration
Bryan C. Steverson
Judith Heerwagen, PhD

Submitted by:

Lighting Research Center
Rensselaer Polytechnic Institute

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LIGHTING RESEARCH CENTER
21 UNION STREET
TROY, NY 12180

WWW.LRC.RPI.EDU

EXECUTIVE SUMMARY

Lighting design for office buildings has focused largely on the amount of light needed for work, strategies to reduce visual discomfort, and the use of daylight as a means to reduce energy in buildings. However, the lighting characteristics affecting the biological clock are different than those affecting the visual system. Little attention has been given to understanding how light affects occupants' psychological and physiological systems, including circadian functions that regulate sleep, mood, and alertness. Daylight is an ideal light source for the circadian system, but it is not known whether those who work in spaces that have daylight are indeed receiving enough light to promote circadian entrainment while in their office spaces.

Researchers from the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute, together with U.S. General Services Administration (GSA) staff assessed office occupants' experience of light to identify health outcomes linked to measured light exposure. If health benefits are identified, this could have far-reaching effects on sustainable lighting design as not just a means to achieve energy efficiency goals but a means to enhance the health and wellbeing of federal workers, improve overall work effectiveness, and reduce long term health problems associated with circadian disruption (including sleep problems, mood disorders, and cardiovascular impacts). Furthermore, new technologies such as LED lighting could enable greater control over both the amount of light and its spectral characteristics, both of which are known to influence circadian processes and health outcomes in experimental settings.

Presented here are data from 17 participants working at the Federal Center South building in Seattle, WA, who volunteered to repeat the study in the summer months, complied with the study protocol, and had usable data. Participants agreed to wear the Daysimeter, a calibrated light and activity meter, for seven consecutive days during the months of June, July, and August 2015. Daysimeters measure continuous light exposures, allowing researchers to perform calculations of how much light that is effective for the circadian system (i.e., circadian stimulus, or CS) the occupants of the building may be receiving. Participants wore the Daysimeter while awake and during sleep, and also filled out a series of self-reports probing their sleep quality, depression, and mood scores.

Results during the summer months showed that the CS during the work days in the office experienced by participants was between 0.20 and 0.37, with mean ± standard deviation (SD) = 0.29 ± 0.08. This is significantly higher than exposures experienced during the winter months, when participants were exposed to CS values between 0.15 to 0.24, with a mean ± SD = 0.19 ± 0.06. In general, those sitting closer to windows and in the north, then northeast and east facades received the highest CS values and those sitting away from windows received the lowest CS values. Unlike with the winter data, the present data did not show that participants in this building were exposed to the highest CS values during their working hours, compared to when at home (early morning and evenings). Mean ± SD CS values pre-, during, and post work in summer months were 0.25 ± 0.07, 0.29 ± 0.08, and 0.27 ± 0.09, respectively.

In terms of photopic lux, the geometric mean of the light levels experienced by participants while at work was 256 lux (100 lux in winter) and the arithmetic mean was 1000 lux (265 lux in winter). As shown, photopic light exposures in the summer were

significantly higher than in winter months. These values were similar to those from participants at the Edith Green-Wendell Wyatt Federal Building in Portland, OR.

Phasor magnitudes using data for 7 days were used as a measure of circadian entrainment. It quantifies circadian entrainment/disruption in terms of phase and amplitude relationships between measured light-dark and activity-rest patterns. Phasor magnitudes (mean = 0.30) were slightly lower than in winter months (mean = 0.31) and lower than what the LRC has measured in other dayshift workers (e.g., teachers or nurses), which had mean phasors of 0.4 to 0.5 (Rea et al. 2011; Miller et al. 2010). Phasor magnitude measured in other Federal buildings in Portland, OR, and in Grand Junction, CO, in the summer was 0.36.

Participants working in the Federal Center South building slept on average 6.1 hours in summer (mean sleep in winter was 5.9 hours), had a sleep onset latency of about 21 minutes (24 minutes in winter) and a sleep efficiency of 79% (77% in summer), similar to those in the Edith Green-Wendell Wyatt Federal Building in Portland, OR and the GSA Central Office Building in Washington, DC. Pittsburgh Sleep Quality Index (PSQI) scores in participants in the Federal Center South building were close to 7 (no change from winter data), indicating sleep disturbances in this group. The mean PROMIS Global Score, another scale probing sleep disturbances, was below 25 (mean = 20 in winter and mean = 19 in summer) indicating no sleep disturbances in this population. None of the participants reported being clinically depressed or stressed and no significant changes in mood scales were observed between winter and summer. These results were also found in another building in the northwest (Edith Green-Wendell Wyatt Federal Building in Portland, OR), suggesting that those who live in the northwest may adapt better to lower light availability.

It is not known whether the circadian system will adapt to lower light levels and whether this stimulus, given that it was the strongest participants received during the day, would be sufficient to maintain entrainment to the 24-hour solar day.

BACKGROUND

Lighting design for office buildings has focused largely on the amount of light for work, strategies to reduce visual discomfort, and the use of daylight as a means to reduce energy in buildings. Little attention has been given to understanding the experience of light, especially how it affects occupants' psychological and physiological systems, including circadian functions that regulate sleep, mood, alertness, and seasonal affective disorder (SAD).

It is well known that people like daylight in their work environment (Boyce et al. 2003; Cuttle 1983; Heerwagen & Heerwagen 1986; Hopkinson & Kay 1969). It has been argued that daylight also positively affects performance (Heschong Mahone Group 1999, 2003a, 2003b), but a cause-and-effect mechanism relating daylight to good performance has never been shown. Daylight is certainly not a special light source for vision, and the link between improved psychological wellbeing and improved performance cannot be reliably shown (Boyce 2004; Boyce & Rea 2001). But another line of research has emerged in the last 30 years, one potentially providing a physiological foundation for the widely accepted, yet again, undocumented belief that daylight improves productivity.

Basic research in circadian photobiology (Arendt 1995; Klein 1993; Moore 1997; Turek & Zee 1999) suggests that light plays a very important role in regulating the circadian (approximately 24-hour) patterns of human behavior by directly affecting the internal timing mechanisms of the body (Jewett et al. 1997; Lewy et al. 1982; Turek & Zee 1999; Van Someren et al. 1997). In contrast to the visual system, however, the circadian system requires higher light levels and shorter wavelength (i.e., blue) light to be activated (Brainard et al. 2001; McIntyre et al. 1989; Thapan et al. 2001). Moreover, since humans evolved under patterns of daylight and darkness, it is conceivable that the physical characteristics of daylight (i.e., quantity, spectrum, distribution, timing, and duration) might be fundamentally important to the regulation of human performance through the circadian system (Rea et al. 2002).

Light exposure through retinal non-visual pathways is an important regulator of circadian functions. Via the retinohypothalamic tract (RHT), neural signals are sent to the biological clock located in the suprachiasmatic nuclei (SCN). To regulate circadian functions such as body temperature, melatonin production, sleep, and activity-rest behavior, the SCN sends neural signals to other regulatory neural structures in the brain, most notably the pineal gland that stops production of the hormone melatonin when the retina is exposed to sufficient light at night. Light is the primary stimulus for regulating, through the SCN, the timing and the amount of melatonin produced by the pineal gland at night and, presumably, its effects on integrated behaviors such as subjective alertness and performance. When considering the importance of light to the circadian system and the lighting characteristics affecting it, daylight is a remarkably ideal light source for the circadian system.

Since light plays an important role in regulating human behavior through this circadian clock, daylight acting on the circadian system could conceivably positively affect performance. Current electric lighting is manufactured, designed and specified only to meet visual requirements, so daylight in buildings may indeed provide a special light source for driving and regulating human circadian behavior because it is dominated by short-wavelength radiation and has a high intensity. Furthermore, the use of new technologies such as LED lighting can enable greater control over both the amount of light and its spectral characteristics, both of which are known to influence circadian processes and health outcomes in experimental settings. Thus, it is reasonable to pursue the hypothesis that daylight might improve health and wellbeing through the circadian system, or, conversely, that chronic lack of daylight exposure during daytime hours may be promoting circadian disruption and negatively affecting health and mood.

However, there are no data currently available on the light-dark exposure patterns in people working in buildings that were designed to utilize daylight. Therefore, the overarching goal of this research is to assess occupant experience of light and to identify health outcomes linked to measured light exposure. If health benefits are identified, this could have far-reaching effects on sustainable lighting design as a means to achieve energy goals as well as to enhance the health and wellbeing of federal workers, improve overall work effectiveness, and reduce long term health problems associated with circadian disruption (including sleep problems, mood disorders, and cardiovascular impacts).

METHODS

PARTICIPANT RECRUITMENT

All participant recruitment was performed by GSA staff that did not have a direct working relationship with the employees. GSA staff sent out emails and organized informational sessions at the building during lunchtime hours. There were no exclusion criteria to participate in the study. Two informational sessions were held in December 2014. All interested parties were invited to attend and ask questions about the research protocol. If interested, participants contacted LRC staff and signed up for the study. A GSA employee was the point person on site and distributed and collected all the devices and questionnaires. The LRC was able to recruit 20 participants; 17 participants (14 female, 3 male) completed the study and had usable data. Average age of the participants was 46.7 years ± SD 11.9 years; average chronotype was 2.9 ± SD 2.0.

MEASUREMENT PROCEDURES

DEVICES

The Daysimeter, a calibrated light measuring device, was used to collect personal light and activity data. Light sensing by the Daysimeter is performed with an integrated circuit (IC) sensor array (Hamamatsu model S11059-78HT) that includes optical filters for four measurement channels: red (R), green (G), blue (B), and infrared (IR) (Figueiro et al. 2013). The R, G, B, and IR photo-elements have peak spectral responses at 615 nanometers (nm), 530 nm, 460 nm, and 855 nm, respectively. The Daysimeter is calibrated in terms of orthodox photopic illuminance (lux) and of circadian illuminance (CL_A). CL_A calibration is based upon the spectral sensitivity of the human circadian system. From the recorded CL_A values, it is then possible to determine the magnitude of circadian stimulus (CS), which represents the input-output operating characteristics of the human circadian system from threshold to saturation. Briefly, illuminance is irradiance weighted by the photopic luminous efficiency function ($V(\lambda)$), an orthodox measure of the spectral sensitivity of the human fovea, peaking at 555 nm. CL_A is irradiance weighted by the spectral sensitivity of the retinal phototransduction mechanisms stimulating the response of the biological clock, based on nocturnal melatonin suppression. CS is a transformation of CL_A into relative units from 0, the threshold for circadian system activation, to 0.7, response saturation, and is directly proportional to nocturnal melatonin suppression after one hour exposure (0% to 70%).

Recordings of activity-rest patterns were based upon the outputs from three solid-state accelerometers calibrated in g-force units (1 g-force = 9.8 m/s) with an upper frequency limit of 6.25 Hz. An activity index (AI) is determined using the following formula:

$$AI = k\sqrt{(SS_x + SS_y + SS_z)/n}$$

SS_x, SS_y, and SS_z are the sum of the squared deviations from the mean of each channel over the logging interval, n is the number of samples in a given logging interval, and k is a calibration factor equal to 0.0039 g-force per count. Logging intervals for both light and activity were set at 90 seconds.

The goal of collecting personal light exposures from the workers is related to the effects of light on circadian rhythms. Circadian rhythms are every rhythm in our body that oscillates with a period close to 24 hours, and this 24-hour oscillation repeats daily. An example of a robust circadian rhythm is the production of the hormone melatonin by the pineal gland. Melatonin is always released in the bloodstream at night and under conditions of darkness, and signals darkness to the body. Peak melatonin levels occur in the middle of the night, while the trough occurs in the middle of the day. In the absence of external cues, such as light-dark patterns, circadian rhythms will run with an average period of 24.2 hours; as a consequence, the peak and trough of melatonin would occur 10-15 minutes later every day. Morning light resets our biological clock daily and entrains us to the 24-hour solar day. Lack of entrainment has been associated with circadian disruption, which means that the peaks and troughs of various circadian rhythms are occurring at times in which it should not be occurring (e.g., melatonin levels are peaking during the daytime). Furthermore, the lighting characteristics affecting the biological clock are different than those affecting the visual system. In brief, humans need at least 10 times more light to activate their circadian system than to see. Light levels used in offices (e.g., 500 lux [approx. 50 footcandles (fc)] on the work plane; about 100-200 lux [approx. 10-20 fc] at the cornea) are sufficient for a person to read black fonts on white paper, but only slightly affect the biological clock. The biological clock is sensitive to blue light (460 nm), while one aspect of the visual system (i.e., acuity) is maximally sensitive to yellow-green (555 nm). The biological clock cares about when people are exposed to light over the course of the 24-hour day. Morning light will help a person go to bed earlier and wake up earlier while evening light will help a person go to bed later and wake up later. Therefore, being able to measure light that affects the circadian system using a calibrated device, and more importantly, being able to know when a person is exposed to circadian light over the course of the 24-hour period is crucial. The Daysimeter serves this purpose.

QUESTIONNAIRES

Participants completed several subjective questionnaires about mood and sleep habits at the start of the study: Pittsburgh Sleep Quality Index, Karolinska Sleepiness Scale, PROMIS sleep disturbance, Positive and Negative Affect Schedule, Perceived Stress Scale, and Center for Epidemiologic Studies Depression Scale.

The Pittsburgh Sleep Quality Index (PSQI): Subjective measure of sleep quality and patterns. It differentiates poor from good sleep by measuring seven areas: subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, use of sleep medication, and daytime dysfunction. Scoring of answers is based on a 0 to 3 scale and yields one global score. A global score of 5 or greater indicates a poor sleeper. (Buysse et al. 1989)

Karolinska Sleepiness Scale (KSS): Self-assessment of subjective sleepiness. The scale ranges from 1 to 9, with 1 = most alert and 9 = fighting sleep. (Åkerstedt and Gillberg 1990)

PROMIS Sleep Disturbance-Short Form 8a: Eight questions regarding sleep quality (e.g., my sleep was refreshing, I had difficulty falling asleep, my sleep was restless...) on a scale of 1 to 5 (1 = very much, 2 = quite a bit, 3 = somewhat, 4 = a little bit, 5 = not at all). (Cella et al. 2010)

Positive and Negative Affect Schedule (PANAS): 10 positive affects (interested, excited, strong, enthusiastic, proud, alert, inspired, determined, attentive, and active) and 10 negative affects (distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, and afraid). Participants are asked to rate items on a scale from 1 to 5, based on the strength of emotion where 1 = very slightly or not at all and 5 = extremely. (Watson et al. 1988)

Perceived Stress Scale (PSS): Measure of the degree to which situations in one's life are appraised as stressful. Items were designed to assess how unpredictable, uncontrollable, and overloaded respondents find their lives to be. The scale also includes a number of questions about current levels of experienced stress. The questions in the PSS ask about feelings and thoughts during the last month. In each case, respondents are asked how often they felt a certain way (0 = never, 1 = almost never, 2 = sometimes, 3 = fairly often and 4 = very often). (Cohen et al. 1983)

Depression Scale (CES-D): Self-report designed to measure depressive symptoms. This test is a 20-item measure that asks how often over the past week the participants experienced symptoms associated with depression, such as restless sleep, poor appetite, and feeling lonely. Response options range from 0 to 3 for each item (0 = rarely or none of the time, 1 = some or little of the time, 2 = moderately or much of the time, 3 = most or almost all the time). Scores range from 0 to 60, with high scores (greater than 16) indicating greater depressive symptoms. (Radloff 1977)

PROTOCOL

Participants signed a consent form approved by the Institute Review Board at Rensselaer Polytechnic Institute. Once enrolled in the study, participants were asked to wear the Daysimeter as a pendant for 7 consecutive days during winter months (between June and August 2015). At night while sleeping, participants were asked to wear the device on their wrist to monitor their activity-rest patterns.

During the 7-day data collection period, participants were asked to keep a sleep log of bedtime and wake time, sleep latency, quality of sleep, and naps. KSS data were collected 4 times per day: wake, noon, dinner, and bedtime.

The devices were mailed to the GSA staff volunteer helping with the study. She distributed and collected all of the devices but did not have access to any data. All of the devices and questionnaires were placed inside a sealed envelope and the GSA staff was only responsible for giving the envelope to the participant at the start of the study and receiving the envelope at the end of seven days. No issues were reported with this method of delivering/returning the devices to the LRC.

DATA ANALYSES

The Daysimeter data were analyzed and the following outcome measures were obtained:

PHOTOPIC LIGHT AND CIRCADIAN STIMULUS

In terms of photopic light levels, the LRC calculated these values in two ways: 1) geometric mean of the recorded levels were calculated to help normalize the highly skewed distribution of recorded light levels and 2) arithmetic mean, which are generally higher because of the highly skewed values, such as a trip outdoors during the daytime. In terms of circadian light exposures, we calculated the overall circadian light exposures during the study, as well as the circadian stimulus during working hours (assumed to be between 8:00 a.m. and 5:00 p.m.) and outside working hours (early morning after waking and evening prior to bedtimes) on days that participants were in the building.

PHASOR MAGNITUDE AND PHASOR ANGLE

Rea et al. (2008) proposed a quantitative technique to measure circadian disruption, known as phasor analysis, which quantifies circadian disruption in terms of the phase and the amplitude relationships between the environmental light-dark pattern and behavioral response patterns. Phasor analysis makes it possible to interpret the light and activity data, sampled together over consecutive multiple days. To quantify circadian disruption using the Daysimeter data, the LRC used the measured circadian light-dark pattern and activity-rest pattern. Phasor analysis incorporates a fast Fourier transform (FFT) power and phase analysis of the circular correlation function computed from the two sets of time-series data. Conceptually, each data set is joined end-to-end in a continuous loop. Correlation values (r) between the patterns of light-dark and activity-rest are then computed (e.g., every 5 minutes) as one set of data is rotated with respect to the other. An FFT analysis is then applied to the circular correlation function to determine the 24-hour amplitude and phase relationships between the light-dark data and the activity-rest data. The resulting vector, or phasor, quantifies, in terms of the 24-hour frequency, how closely tied the light and activity patterns are to a 24-hour pattern (phasor magnitude) as well as their relative temporal relationship (phasor angle). Phasor analysis is used to characterize the resonance between the 24-hour light-dark pattern and the 24-hour activity-rest pattern. The overall light level exposures were calculated by creating a mean 24-hour light-dark pattern from the hourly mean values for each participant. Since CS is a measure of the effectiveness of optical radiation on the retina for stimulating the human circadian system, the daily patterns of CS were used in the phasor analyses; the larger the phasor magnitude, the greater the resonance between these two rhythms.

While the Daysimeter devices were worn on the wrist during the nighttime, only the daytime (pendant) data were included in the phasor analyses. This was because the activity patterns differ from when the device is worn as a pendant to when it is worn on the wrist; therefore, to avoid bias in the data, researchers assumed close to zero activity and light during the times at which participants reported being asleep. This allowed a comparison of the phasor analyses from these participants to other data that were already collected.

ACTIVITY-REST RHYTHMS CONSOLIDATION

The two computed measures of activity-rest rhythms consolidation were: 1) inter-daily stability (IS), a ratio indicating the strength of coupling between the light-dark cycle and activity-rest rhythm over a 24-hour period; 2) intra-daily variability (IV), an indication of the fragmentation of the activity-rest rhythm (Van Someren et al. 1997).

SLEEP ANALYSES

The sleep algorithm is based on the sleep analyses used by the Actiwatch Algorithm (Actiware-Sleep Version 3.4; Mini Mitter Co., Inc., now Philips Respironics). The algorithm developed for the Daysimeter data scores each data sample as “sleep” or “wake” based on the AI, the delta of the root mean square of acceleration recorded by the Daysimeter averaged over the sampling interval or epoch of 90 seconds. All of the following sleep measures using the Daysimeter data were based upon this binary sleep-wake score.

The following sleep parameters were calculated from the activity-rest data obtained with the nighttime Daysimeter:

- Time in bed is defined as the difference between wake time and bedtime.
- Sleep start time is defined as the first 10-minute interval within the analysis period with one or less epochs scored as wake.
- Sleep end time is defined as the last 10-minute interval within the analysis period with one or less epochs scored as wake.
- Assumed sleep time is then found to be the difference between sleep end time and sleep start time.
- Actual sleep time is defined as the sum of epochs scored as sleep multiplied by the epoch length.
- Actual sleep time percent is simply the actual sleep time divided by the assumed sleep time.
- Actual wake time is calculated as the sum of epochs scored as wake multiplied by the epoch length.
- Actual wake time percent is the actual wake time divided by the assumed sleep time.
- Sleep efficiency is the percentage of time in bed that is spent sleeping, or actual sleep time divided by time in bed.
- Sleep onset latency is the period of time required for sleep onset after going to bed, calculated as the difference between sleep start and bedtime.

RESULTS

Table 1 shows the mean, median and standard deviation (SD) summer values for overall light exposures during 7 days (waking average) as well as the light exposures prior to, during and after working hours for the days in which participants were at work (excludes weekends). Please note that due to poor compliance, one participant was removed from the analyses (Daysimeter data included 18 participants) and some of the participants had fewer than 7 days. Table 2 shows the same type of data for phasor and sleep analyses from the Daysimeter data. Table 3 shows the self-reported sleep and mood questionnaires. Table 4 shows the data grouped by building orientation, floors, and distance from windows. For reference, winter data are also included.

A few interesting observations from the data:

- The mean waking CS value measured during the summer months was 0.27, significantly higher than the mean waking CS value measured during the winter months (mean = 0.15). The mean CS value experienced by participants during their working hours (between 8:00 a.m. and 5:00 p.m.) was 0.29, which was also significantly higher than the CS value measured during winter months (mean = 0.19). The CS of 0.29 is equivalent to 29% melatonin suppression if the light experienced was applied for 1 hour in the middle of the night, when melatonin levels are high. We originally hypothesized that a good stimulation for the circadian system would be 0.3 or greater for a period of 1 hour. Given that participants are exposed to this CS value for periods longer than 1 hour, it may be possible that a CS value of 0.1 or higher is enough to maintain entrainment. Based on our data from acute melatonin suppression studies, the threshold for activation of the circadian system is 0.1. While entrainment of the circadian system is not the same as acute melatonin suppression, there is not a strong reason to believe that acute melatonin suppression and circadian entrainment have different sensitivities to light.
- CS values were the highest in seating positions close to windows and located in the north-northwest, than in the northeast and north facades. Those sitting close to windows received a mean CS of 0.32-0.34, while those sitting away from windows received CS values as low as 0.23.
- Phasor magnitudes were lower than the other groups of workers but higher than those measured in other Federal workers (mean = 0.30 in summer and 0.31 in winter months). A high phasor magnitude suggests that the person is entrained to the 24-hour day/night cycle. For comparison, our other data sets show that the mean phasor magnitude in school teachers and dayshift nurses was 0.52 and 0.46 respectively (Rea et al. 2011; Miller et al. 2010). These are, however, very regular workers because both dayshift nurses and teachers have strict schedules.
- Mean phasor angle was 0.46 (winter mean phasor angle was 1.48). This lower phasor angle in summer months compared to winter months is very typical, a result of higher circadian light availability during summer evenings. Because daytime workers have some activity later in the evening and because in winter months there is no daylight availability in the evening, the phasor angles tend to be higher than in summer months, when there is daylight during part of the evening hours. These values are similar to those obtained in summer months in the other Federal buildings we studied.

- Based on the actigraphy data from the Daysimeter, the average sleep amount (mean = 6.3 hours) in this group of workers is consistent with data from the other Federal buildings, although the sleep duration in those working at Federal Center South was greater than in those working on the other buildings. Sleep efficiency was also low, similar to sleep efficiency in participants from other Federal buildings (mean = 79% in summer and mean = 79 in winter months). Mean sleep onset latency was similar to those in other buildings that had similar CS values (mean = 21 minutes in summer and 24 minutes in winter months).
- Sleep scores from self-reports were again mixed. The mean PSQI global score was 6.6 (the mean in the winter month was 7), suggesting that on average this group has sleep disturbances (7 out of 19 participants had scores above 6, 2 out of 19 had a score of 6 and 10 out of 19 participants had scores below 6). Similar to the winter months, the PROMIS Global Score suggests that only one of the participants had sleep disturbances (means score = 20 in winter and mean score = 19 in summer; scores above 25 signify sleep disturbances). Nine participants were at or above a score of 20.
- Depression scores were low for all participants (mean score = 6.5 in summer and mean score = 6 in winter months). Average perceived stress was within the normal values (mean score = 13 in both seasons) as well as PANAS positive and PANAS negative.
- KSS score (sleepiness) followed an expected pattern that was also observed in winter months, that is, participants reported being more tired at waking and bedtimes than during the middle of the day.

Some limitations of the data set include:

- It is not known whether participants' life events are playing a stronger role in their self-report ratings than their personal light exposures. The LRC did not set out to investigate other factors.
- Research questions still unanswered are whether humans adapt to lower levels of light for the circadian system, and whether a CS value of 0.15-0.2 may be enough to maintain entrainment. In addition, it is not known whether an 8-hour exposure to this CS value is also sufficient for entrainment. We do know, however, that using data from various laboratories, the threshold for activation of the circadian system, as measured by acute melatonin suppression is 0.1.

Figure 1 shows mean CS and activity over the course of the seven days for the participants at the Federal Center South building. This figure can be seen as a "sketch" of the participants' CS and activity over the course of 24 hours. As shown in the figure, participants were regular and exposed to similar lighting conditions over the course of seven days. Participants received the higher amounts of circadian light during working hours. As with other populations, activity levels over the course of seven days are higher during the daytime and evening hours (black traces on graphs), while light exposures tend to be higher around the middle of the day and lower in the early morning and evening hours. This explains the high phasor angle observed in this population.

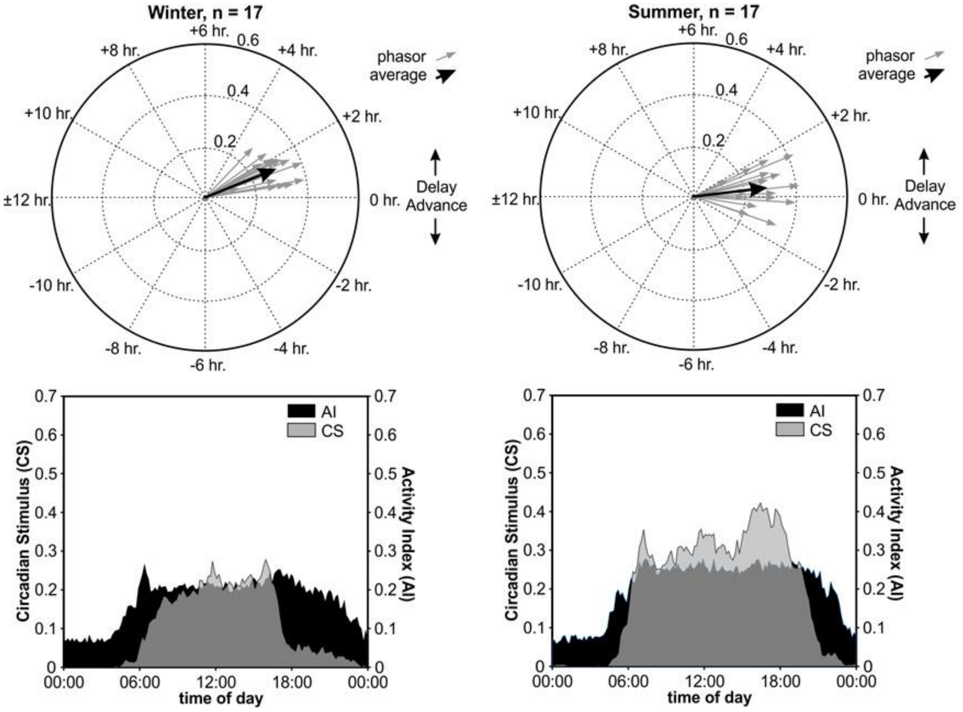

Figure 1. Phasor diagrams for winter (left) and summer (right) for the 17 repeating participants who had usable data. Phasor magnitude (length) quantifies, in terms of the 24-hour period, how closely tied the light-dark and activity-rest patterns are to the 24-hour day and the angle quantifies the relative phase of the light-dark and activity-rest patterns. Bottom graphs: Average circadian stimulus (CS) and activity index (AI) for the 17 repeating participants who had usable data..

DISCUSSION

Daylight is a remarkably ideal light source for the circadian system. Thus, it is reasonable to pursue the hypothesis that daylight might improve health and wellbeing through the circadian system, or, conversely, that chronic lack of daylight exposure during daytime hours may be promoting circadian disruption and negatively affecting health and mood. The first step toward forging a link between daylight exposure in buildings and health outcomes is to measure patterns of circadian light and dark experienced by workers in the building. This can help quantify how occupant behavior or design modifications affect personal light exposures at work. The present study adds data to our previous studies by obtaining circadian light-dark and activity patterns in office workers in another Federal building designed to increase daylight availability in the space.

Given that all the current lighting standards are designed to meet the needs of the visual system, and that the human visual system is much more sensitive to light than the human circadian system, it was important to use a calibrated light meter that would provide measurements of circadian stimulation from occupants of the buildings. The fact that a person can see in the environment does not necessarily mean that the circadian system is being stimulated. Moreover, the spectral sensitivity of the circadian system peaks at short wavelengths (i.e., blue light: close to 460 nm) while the peak sensitivity of the human visual system is close to 555 nm.

Based on our measurements, participants in the Federal Center South building are being exposed to CS values between 0.15 and 0.27 during the working day in winter months, with the exception of two participants who were sitting away from windows and that were exposed to CS below 0.1. In summer, the average CS values were significantly higher than in winter months. In general, CS stimulus in those working in this building are comparable or in some cases, slightly higher than those measured from participants working at the other studied sites. The pattern of light availability is consistent with other buildings, where deskspaces located near the windows and the atrium received the highest CS values and those located furthest from the windows received the lowest CS values. In winter, those working on the 1st and 3rd floors received higher CS (mean CS = 0.18 and 0.22, respectively) than those working on the 2nd floor (mean CS = 0.16). In summer, those working on the 2nd and 3rd floors received higher CS (mean = 0.25 and 0.32, respectively) than the one participant working on the 1st floor (mean = 0.2). These results should be considered with caution because there was only one participant on the 1st floor.

One remarkable difference between winter and summer light exposure was the much higher CS values measured pre- and post-work during the summer. While workers were exposed to very little light before and after coming to work during winter, this distinction was lost in summer months. Activity was also slightly higher in summer, but this difference was not statistically significant.

Although we did not observe any strong correlations between CS and self-reports of mood and sleep disorders, it is possible that the use of a larger control group receiving even lower CS values would allow us to determine whether there is a correlation between circadian light exposures at work and self-reports of sleep and mood. Objectively, not inconsistent with measurements in other Federal buildings, most of the individuals who participated in the study slept less than 8 hours per night and had lower sleep efficiency than would be expected from healthy individuals. This group, however, had the greatest sleep duration of all the other building participants.

While the threshold for activation of the circadian system is not yet determined, data from our laboratory and other laboratories point to a CS value of 0.1 as the threshold value. That being the case, the lack of mood issues is consistent with the fact that workers do receive light above threshold in the building. Another possible explanation for these results, which are consistent with those observed at the Edith Green-Wendell Wyatt Federal Building in Portland, OR, is that those living in the northwest, which tends to have a greater number of darker and gloomier days both in winter and summer than, for example, Grand Junction, CO, are more adjusted to these darker days and are less sensitive to the lack of light typically observed in winter months. This hypothesis should be formally tested in future studies.

Table 1. Mean, median and standard deviation (SD) waking, pre-work, work and post-work averages from the Daysimeter data.

Winter	Waking Average			Pre-Work Average			Work Average			Post-Work Average		
	Ari-mean (CS)	Illuminance Ari-mean (Lx)	Illuminance Geo-Mean (Lx)	Ari-Mean (CS)	Illuminance Ari-Mean (Lx)	Illuminance Geo-Mean (Lx)	Ari-Mean (CS)	Illuminance Ari-Mean (Lx)	Illuminance Geo-Mean (Lx)	Ari-Mean (CS)	Illuminance Ari-Mean (Lx)	Illuminance Geo-Mean (Lx)
Mean	0.15	407	31	0.09	218	18	0.19	265	100	0.09	173	14
Median	0.14	287	30	0.06	68	9	0.20	225	96	0.10	107	12
SD	0.05	318	23	0.09	544	32	0.06	176	68	0.04	163	13
p-value	<0.001	<0.001	<0.001	<0.001	0.02	0.002	<0.01	<0.001	<0.001	<0.001	<0.001	0.02

Summer	Waking Average			Pre-Work Average			Work Average			Post-Work Average		
	Ari-mean (CS)	Illuminance Ari-mean (Lx)	Illuminance Geo-Mean (Lx)	Ari-Mean (CS)	Illuminance Ari-Mean (Lx)	Illuminance Geo-Mean (Lx)	Ari-Mean (CS)	Illuminance Ari-Mean (Lx)	Illuminance Geo-Mean (Lx)	Ari-Mean (CS)	Illuminance Ari-Mean (Lx)	Illuminance Geo-Mean (Lx)
Mean	0.27	1783	140	0.25	812	128	0.29	1000	256	0.27	2589	190
Median	0.28	1561	127	0.23	629	86	0.28	848	253	0.24	1997	83
SD	0.05	824	79	0.07	801	116	0.08	656	120	0.09	1890	269
p-value	<0.001	<0.001	<0.001	<0.001	0.02	0.002	<0.01	<0.001	<0.001	<0.001	<0.001	0.02

Table 2. Phasor and sleep analyses from Daysimeter (worn during working days)

	Phasor		Sleep		
Winter	Magnitude	Angle (hours)	Actual Sleep Time (min)	Sleep Efficiency (%)	Sleep Onset Latency (min)
Mean	0.31	1.48	365	78%	27
Median	0.32	1.44	374	80%	11
SD	0.07	0.71	48	10%	50
p-value	0.76	<0.001	0.83	0.54	0.70

	Phasor		Sleep		
Summer	Magnitude	Angle (hours)	Actual Sleep Time (min)	Sleep Efficiency (%)	Sleep Onset Latency (min)
Mean	0.30	0.46	367	79%	23
Median	0.31	0.40	374	79%	19
SD	0.08	0.97	52	8%	14
p-value	0.76	<0.001	0.83	0.54	0.70

Table 3. Self-reports of mood, sleep and depression

Winter	Total CES-D	PSQI	PSS-10	Sleep Disturbance (t-score)	PANAS (total positive)	PANAS (total negative)
Mean	5.94	6.88	13.59	50.48	30.59	14.65
Median	6.00	6.00	14.00	50.20	32.00	13.00
SEM	0.75	0.59	1.34	1.06	1.59	0.94
p-value	0.33	0.91	0.96	0.52	0.68	0.59

Summer	Total CES-D	PSQI	PSS-10	Sleep Disturbance (t-score)	PANAS (total positive)	PANAS (total negative)
Mean	6.94	6.94	13.65	51.46	31.35	15.12
Median	6.00	7.00	15.00	52.40	32.00	15.00
SEM	1.02	0.76	1.72	1.26	1.78	0.94
p-value	0.33	0.91	0.96	0.52	0.68	0.59

Table 4. Summary of floor, window proximity and building orientation (winter)

location			phasor analyses		overall waking average				pre-work average			
			magnitude	angle (hours)	Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean	Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean
Sort by floor	Floor 1	(n=1)	0.35	0.58	0.14	150	53	0.15	0.04	41	9	0.17
	Floor 2	(n=9)	0.28	1.40	0.12	270	23	0.22	0.06	76	9	0.23
	Floor 3*	(n=15)	0.33	1.43	0.17	604	36	0.21	0.10	262	15	0.23
Sort by proximity to window (1=closest; 4=furthest)	1*	(n=9)	0.34	1.21	0.18	684	44	0.20	0.08	105	20	0.24
	2*	(n=8)	0.29	1.66	0.11	249	25	0.22	0.06	101	10	0.21
	3	(n=6)	0.30	1.41	0.16	508	22	0.24	0.10	451	6	0.25
	4	(n=2)	0.32	1.00	0.14	219	38	0.18	0.09	103	11	0.19
Sort by window orientation	E	(n=4)	0.33	1.23	0.19	733	22	0.21	0.14	618	15	0.21
	N*	(n=5)	0.32	1.32	0.17	880	45	0.18	0.11	273	18	0.24
	NNE	(n=1)	0.35	1.99	0.15	236	59	0.22	0.09	96	22	0.23
	NNW	(n=3)	0.28	1.86	0.11	185	11	0.23	0.07	64	10	0.24
	S*	(n=11)	0.32	1.33	0.13	292	32	0.23	0.05	42	9	0.23
	W	(n=1)	0.29	0.91	0.17	303	38	0.15	0.05	73	11	0.23

*Contains data from a small number of devices that still require calibration

Table 4. (winter - cont.)

location			work average				post-work average			
			Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean	Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean
Sort by floor	Floor 1	(n=1)	0.18	136	112	0.14	0.10	100	36	0.17
	Floor 2	(n=9)	0.16	189	77	0.23	0.07	87	11	0.22
	Floor 3*	(n=15)	0.22	343	134	0.19	0.09	226	13	0.22
Sort by proximity to window (1=closest; 4=furthest)	1*	(n=9)	0.24	394	166	0.19	0.10	267	17	0.19
	2*	(n=8)	0.15	215	85	0.20	0.05	84	8	0.22
	3	(n=6)	0.19	230	73	0.23	0.11	167	11	0.25
	4	(n=2)	0.17	175	97	0.19	0.09	103	22	0.18
Sort by window orientation	E	(n=3)	0.24	306	148	0.19	0.14	423	16	0.22
	N*	(n=5)	0.21	431	114	0.17	0.10	216	13	0.19
	NNE	(n=1)	0.23	289	181	0.22	0.05	43	18	0.22
	NNW	(n=3)	0.17	244	94	0.24	0.05	60	5	0.22
	S*	(n=11)	0.18	203	95	0.22	0.07	96	14	0.23
	W	(n=1)	0.27	350	141	0.15	0.11	222	16	0.15

*Contains data from a small number of devices that still require calibration.

Table 4. Summary of floor, window proximity and building orientation (summer)

location			phasor analyses		overall waking average				pre-work average			
			magnitude	angle (hours)	Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean	Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean
Sort by floor	Floor 1	(n=1)	0.23	-1.23	0.28	1641	163	0.17	0.23	564	69	0.24
	Floor 2	(n=5)	0.29	0.22	0.26	2179	158	0.29	0.25	1240	170	0.26
	Floor 3*	(n=12)	0.33	0.95	0.28	1573	130	0.24	0.25	810	133	0.23
Sort by proximity to window (1=closest; 4=furthest)	1	(n=7)	0.33	0.73	0.29	1639	143	0.27	0.22	612	76	0.27
	2*	(n=4)	0.38	0.78	0.30	1824	167	0.26	0.26	1157	179	0.20
	3	(n=5)	0.27	0.67	0.24	1658	113	0.25	0.27	704	156	0.24
	4	(n=2)	0.26	-0.19	0.26	2176	140	0.19	0.30	2025	244	0.21
Sort by window orientation	E	(n=3)	0.28	1.33	0.23	977	60	0.24	0.26	498	150	0.22
	N*	(n=3)	0.31	1.74	0.27	1557	137	0.20	0.35	2007	309	0.21
	NE	(n=1)	0.21	0.39	0.27	1228	127	0.18	0.22	595	130	0.22
	NNE	(n=1)	0.31	1.18	0.24	1021	0	0.21	0.24	878	0	0.21
	NNW	(n=3)	0.41	0.57	0.31	1986	183	0.41	0.20	430	69	0.31
	S	(n=6)	0.30	-0.24	0.28	2394	181	0.24	0.24	927	126	0.23
	W	(n=1)	0.32	0.16	0.29	1246	165	0.17	0.17	643	41	0.22

*Contains data from a small number of devices that still require calibration

Table 4. (summer - cont.)

location			work average				post-work average			
			Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean	Ari-mean (CS)	illuminance Ari-mean (Lux)	Illuminance Geo-mean (Lux)	Activity Ari-mean
Sort by floor	Floor 1	(n=1)	0.20	192	138	0.15	0.35	2681	314	0.18
	Floor 2	(n=5)	0.25	880	207	0.31	0.28	3370	219	0.28
	Floor 3*	(n=12)	0.32	1077	300	0.22	0.23	1972	84	0.24
Sort by proximity to window (1=closest; 4=furthest)	1	(n=7)	0.34	1169	322	0.26	0.24	2157	101	0.27
	2*	(n=4)	0.32	1017	285	0.23	0.23	1941	81	0.25
	3	(n=5)	0.24	711	207	0.24	0.26	2737	211	0.25
	4	(n=2)	0.23	853	169	0.19	0.26	3328	168	0.18
Sort by window orientation	E	(n=3)	0.28	591	250	0.19	0.23	1267	84	0.24
	N*	(n=3)	0.30	1249	278	0.16	0.18	1029	50	0.19
	NE	(n=1)	0.33	1133	310	0.15	0.17	1997	28	0.21
	NNE	(n=1)	0.25	1057	164	0.19	0.18	664	54	0.23
	NNW	(n=3)	0.37	1129	353	0.42	0.30	3265	124	0.40
	S	(n=6)	0.26	979	231	0.25	0.29	3726	239	0.23
	W	(n=1)	0.32	542	270	0.14	0.28	1498	126	0.17

*Contains data from a small number of devices that still require calibration

Table 4. (summer - cont.)

location			sleep analyses (work days)					
			actual sleep time (mins.)	actual sleep (%)	actual wake time (mins.)	actual wake (%)	sleep efficiency (%)	sleep onset latency (mins.)
Sort by floor	Floor 1	(n=1)	395	98%	9	2%	91%	4
	Floor 2	(n=9)	374	86%	60	14%	77%	22
	Floor 3	(n=14)	360	89%	44	11%	79%	23
Sort by proximity to window (1=closest; 4=furthest)	1	(n=8)	386	88%	43	10%	81%	22
	2	(n=8)	325	85%	59	16%	74%	30
	3	(n=6)	354	88%	55	13%	76%	21
	4	(n=2)	386	93%	27	6%	88%	8
Sort by window orientation	E	(n=3)	352	90%	41	10%	82%	13
	N	(n=5)	369	88%	52	12%	76%	28
	NE	(n=1)	326	89%	41	11%	75%	19
	NNE	(n=1)	427	93%	31	7%	89%	10
	NNW	(n=3)	366	88%	52	12%	77%	31
	S	(n=11)	362	88%	50	12%	79%	21
	W	(n=1)	412	89%	51	11%	82%	20

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CREDITS

LRC Researchers: Dr. Mariana Figueiro, Dr. Mark Rea, Jennifer Brons

Graphic Designer: Dennis Guyon

Editor: Rebekah Mullaney