# DAYLIGHT IN OFFICE BUILDINGS: IMPACT OF BUILDING DESIGN ON PERSONAL LIGHT EXPOSURES, SLEEP AND MOOD*

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## Abstract

Lighting design for office buildings has focused largely on the amount of light for visibility, 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 how light affects occupants' psychological and physiological systems, including circadian functions that regulate sleep, mood, and alertness. The specific goals of the present study were to: (1) perform photometric measurements at workstations in winter and late spring, and (2) analyze the impacts of personal light exposure on circadian entrainment using a wearable light and activity measurement device. Reported here are the results of the measurements performed during two seasons in a building located in the Northwest region of the United States.

*Keywords*: Light, Daylight, Building Design, Circadian Light, Sleep, Mood

## 1 Background

It is well known that people like daylight in their work environment (Boyce et al., 2003; Cuttle, 1983; Heerwagen and Heerwagen, 1986; Hopkinson, 1969). It has been argued that daylight also positively affects performance (Heschong Mahone Group, 1999; 2003a; b). Daylight is certainly not a special light source for vision, and the link between improved performance cannot be reliably shown (Boyce, 2004; Boyce and Rea, 2001). Another line of research based upon human circadian system response to light may provide insight into the widely accepted, but again undocumented belief that daylight improves productivity as well as health and wellbeing.

Basic research in circadian photobiology (Arendt, 1995; Klein, 1993; Moore, 1997; Turek and Zee, 1999) suggests that light plays a very important role in regulating the daily patterns of human behaviour by directly affecting the internal timing mechanisms of the body (Jewett et al., 1997; Lewy et al., 1982; Turek and Zee, 1999; Van Someren et al., 1997). Examples of circadian rhythms include the daily variations in behavior, like the sleep-wake cycle, hormone production, and core body temperature. Circadian rhythms are generated and regulated by a biological clock located in the suprachiasmatic nuclei (SCN) in the brain. In the absence of external cues, circadian rhythms in humans will run with a period close to, but not exactly 24 hours (in humans, circadian rhythms free run with a period of 24.2 hours on average).

The light-dark patterns on the retina are the main stimuli driving the biological clock to synchronize circadian rhythms to the 24-hour day. Important light characteristics affecting the human circadian system include the spectral power distribution of the light source (amount and spectrum), timing and duration of exposure, spatial distribution, and light history. The circadian system responds to light differently than the visual system. The amount of polychromatic "white" light necessary to activate the human circadian system (≈ 30 lx) is at least 10,000 times greater than the amount needed to stimulate the visual system (≈ 0.001 lx). In terms of spectrum, the circadian system is maximally sensitive to short-wavelength ("blue") light, with a peak spectral

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sensitivity at around 460 nm, while the visual system, as measured in terms of visual performance or acuity, is most sensitive to 555 nm. In terms of temporal characteristics, operation of the visual system does not depend significantly on the timing of light exposure, and thus responds well to a light stimulus at any time of the day or night. Figures 1 and 2 show spectral and absolute sensitivities of the human circadian system based on the proposed model by Rea et al. (2005).

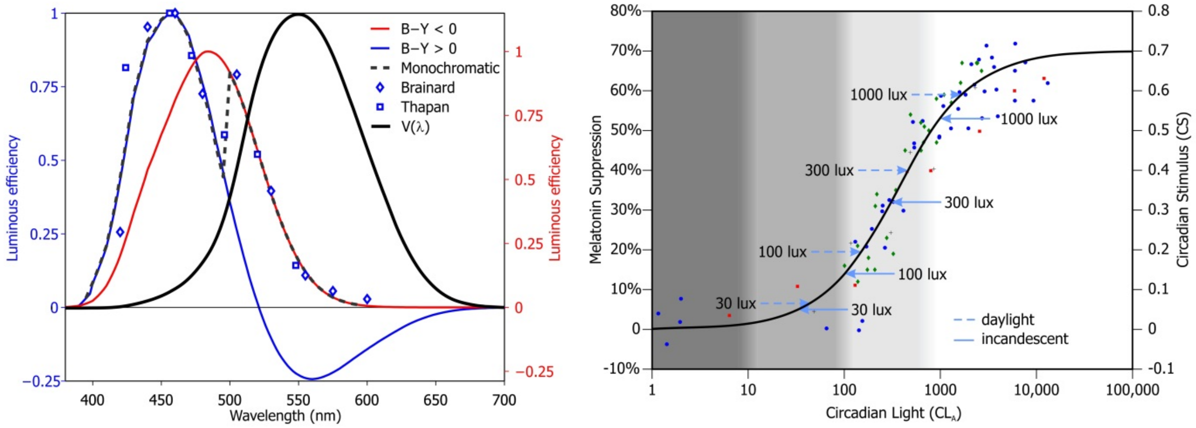

**Figure 1. Left: A selection of spectral sensitivity functions for the human visual and circadian systems. The photopic luminous efficiency function, V(λ), with a peak at 555 nm is shown in black and is a good approximation of the spectral sensitivity of the human fovea for such achromatic tasks such as reading and acuity (Lennie et al., 1993). Three non-linear spectral sensitivity functions for the human circadian system at one light level; each function reflects differences in sensitivity of the human circadian system to different light spectra. The dashed line represents the sensitivity of the human circadian system to individual, narrow-band light spectra as measured in terms of nocturnal melatonin suppression (Brainard et al., 2001; Thapan et al., 2001). The red and the blue curves represent modeled (Rea et al., 2005) spectral sensitivities to "warm" and "cool" polychromatic, "white" light sources, respectively, for a corneal light exposure of one hour at 300 scotopic lx (≈ 150 photopic lx). Right: Input-output response characteristics of the human circadian system. Data from a variety of published studies measuring light-induced nocturnal melatonin suppression were plotted as a function of circadian light ($CL_A$), or circadian illuminance at the cornea (Rea et al., 2010; 2012). Circadian stimulus is proportional to nocturnal melatonin suppression; values range from 0 at or below threshold to 0.7 at or above saturation. Shaded areas represent ranges of common light exposure in $CL_A$.**

The timing of light exposures also affects the circadian system; light can phase advance or phase delay the biological clock. In addition, while the visual system responds to a light stimulus very quickly (less than one second), the duration of light exposure needed to affect the circadian system can take minutes. For the visual system, spatial light distribution is critical (e.g., when reading black letters on white paper), while the circadian system does not respond to spatial patterns. One study showed that light reaching the lower retina is more effective in suppressing melatonin than light reaching the upper retina, but it is not yet well-established how light incident on different portions of the retina will affect the circadian system. It is also important to note that the short-term history of light exposure affects the sensitivity of the circadian system to light; the higher the exposure to light during the day, the lower the sensitivity of the circadian system to light at night.

Irregular light-dark patterns or exposure to light at the wrong circadian time may lead to circadian disruption whereby our biological clock is no longer synchronized with the local sunrise and sunset. Circadian disruption is associated with health risks, including diabetes, obesity, cardiovascular disease, and cancer. Daylight is an ideal light source for synchronizing the circadian system; physically it is of the right amount, spectrum, timing, and duration. In contrast, electric light sources are manufactured, designed, and specified to meet visual requirements, so sufficient daylight in buildings may indeed provide a special light source for driving and regulating the human circadian system. Thus, it is reasonable to pursue the hypothesis that daylight exposure in commercial buildings might be better than all-electric lighting for occupant health and wellbeing.

There are few data currently available on the actual light-dark patterns people are exposed to in commercial buildings that were designed to utilize daylight. Therefore, the overarching goal of this research was to assess occupant exposure to circadian-effective light and investigate whether personal light exposures were linked to health outcomes. If health benefits were identified, this could have far-reaching effects on sustainable lighting design as a means to achieve energy efficiency goals as well as to support the health and wellbeing of workers, improve overall work effectiveness, and reduce long term health problems associated with circadian disruption (including sleep problems, mood disorders, and cardiovascular impacts).

The specific goals of the present study were to: (1) perform photometric measurements at workstations in winter and late spring, and (2) analyze the impacts of personal light exposure on circadian entrainment using a wearable light and activity measurement device for seven days at work and at home. Reported here are the results of the measurements performed during winter and late spring in a building located in the Northwest region of the United States.

## 2 Methods

### 2.1 Building Site

The Edith Green-Wendell Wyatt (EGWW) Federal Building is an 18-story, 525,000 square foot facility in Portland, Oregon, that is the workplace for more than 16 federal agencies and 1,200 federal employees. The building was originally constructed in 1974 and underwent a major renovation between 2009 and 2013.

**Figure 2. The Edith Green-Wendell Wyatt Federal Building exterior, west facade showing sunlight-attenuating reeds, (left) and interior (right).**

EGWW contains open-plan offices with 6-ft partitions and each floor is illuminated by linear fluorescent (T5HO) direct/indirect pendant luminaires (Figure 2). The target illuminance on the work plane in open offices was 30 footcandles (fc), or approximately 300 lux (lx). LED task lights are available to augment the general lighting. The open-plan workstations at EGWW were arranged as two sets of cubicles; one immediately adjacent to windows (window) and the other juxtaposed and closer to the building core (interior). Perimeter windows are tinted (59% visible transmittance, 0.3 solar heat gain coefficient). On the west facade, architectural “reeds” running from the ground to the top floor (Figure 2) provide exterior shading. Manually controlled black mesh shades are provided on all windows.

### 2.2 Photometric Analyses

Photometric measurements were obtained at the two sets of cubicles (window and interior) on three floors (floors 4, 12 and 17) three times per day: morning, midday and afternoon. The cubicles were chosen by the research team as representative of workstations at the four building orientations. Spectral irradiance distribution (SID) measurements were collected using a calibrated spectroradiometer (Ocean Optics model USB650) and then stored on a laptop computer. For each measurement the detector was located and oriented to simulate the position of worker’s eyes while viewing his/her computer monitor.

### 2.3 Daysimeter Protocol

Twenty-four participants working at EGWW agreed to wear the battery-powered Daysimeter (Figueiro et al., 2013), a calibrated light and activity meter, for seven consecutive days during May and June 2014 (late spring) and again during November and December 2014 (winter); all subjects signed a consent form approved by the Institute Review Board at Rensselaer Polytechnic Institute. Participants wore the Daysimeter as a pendant while awake and on the wrist at night while in bed. EGWW building staff volunteers distributed and collected all of the Daysimeters but did not have access to any data. No issues were reported with this method of delivering/returning the devices to the experimenters.

The Daysimeter records and stores light and activity data for up to seven days. 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 ($CL_A$). From the recorded $CL_A$ values, it is then possible to determine the magnitude of circadian stimulus (CS). Briefly, illuminance is irradiance weighted by the photopic luminous efficiency function [V(λ)], 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 non-linear retinal phototransduction mechanisms stimulating the biological clock. 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%) assuming a fixed, 2.3 mm diameter pupil. The Daysimeter also measures rest/activity patterns 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 formula:

$$AI = k\sqrt{[(SSx + SSy + SSz)/n]} \tag{1}$$

SSx, SSy and SSz 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.

### 2.4 Daysimeter Data Analyses

#### 2.4.1 Circadian Stimulus

Average CS values were determined for waking hours. The waking hours included all days, including weekends, when participants wore the device. Average CS during work hours included those data obtained between 8:00 a.m. and 5:00 p.m. Average CS for after-work included those data collected from 5:00 p.m. until self-reported bedtimes.

#### 2.4.2 Phasor Analyses

Rea et al. (2008) proposed a technique to quantify circadian disruption, known as phasor analysis. Phasor analysis utilizes a fast Fourier transform (FFT) power and phase analysis of the circular correlation function computed from the light-dark (measured in terms of CS) and activity-rest (measured in terms of AI) time-series data sets obtained from the Daysimeter. 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 every 5 minutes as one set of data is rotated with respect to the other. An FFT 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 patterns. The resulting vector quantifies the synchrony between the two patterns over 24-hours (phasor magnitude) as well as their phase relationship (phasor angle).

Only the pendant data were included in the phasor analyses because the magnitude of recorded activity is lower when the Daysimeter is worn on the wrist than when it is worn as a pendant. Activity and light were assumed to be at minimum value during the night for the phasor analyses, making it possible to compare the present results with those from other studies.

### 2.4.3 Sleep Analyses

The sleep algorithm for the wrist actigraphy data collected while in bed was 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.

- Actual sleep time was defined as the sum of epochs scored as sleep multiplied by the epoch length.
- Sleep efficiency was the percentage of time in bed that is spent sleeping, or actual sleep time divided by time in bed.
- Sleep onset latency was the period of time required for sleep onset after subject reported going to bed, calculated as the difference between sleep start and bedtime.

## 2.5 Self-reports

During both seven-day data collection periods, participants were asked to fill out a series of self-reports probing their sleep quality, depression and mood. Participants were also asked to keep a sleep log of bedtime and wake time.

The survey instruments included the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989), the Karolinska Sleepiness Scale (KSS) (Åkerstedt and Gillberg, 1990), the PROMIS Sleep Disturbance-Short Form 8a (Cella et al., 2010), the Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988) and the Center for Epidemiologic Studies Depression (CES-D) (Radloff, 1977). The PSQI is a 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 6 or greater indicates a poor sleeper. The KSS is a self-assessment of subjective sleepiness. The scale ranges from 1 to 9, with 1 = most alert and 9 = fighting sleep. KSS data were collected four times per day: wake, noon, dinner, and bedtime. The exact times of the data collection varied between subjects. The PROMIS Sleep Disturbance-Short Form 8a is composed of 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). The PANAS consists of 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." The CES-D: A self-report designed to measure depressive symptoms. This test is a 20-item measure that asks how often over the past week the subjects 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.

## 3 Results and Discussion

### 3.1 Photometric Analyses

Table 1 shows a summary of the photometric measurements.

As expected, exposures to light for the circadian system were higher near the windows than in the interior for both seasons. Interpretation of the measured light levels for different building orientations is more complicated. Oddly, the measured CS value in the north façade was larger in late spring than in winter (CS = 0.49 and 0.34, respectively) but the reverse was true on the south façade (CS = 0.29 in late spring and CS = 0.40 in winter). EGWW is surrounded by other glass-clad, high-rise buildings, so depending upon the sun angle and the reflections off adjacent buildings, workers will occlude direct sunlight with the blinds at otherwise unexpected times of the year. In fact, when making the spot measurements, researchers often observed glaring reflections off the nearby glass-clad buildings. In addition, cloud conditions can contribute to these differences. In general, these spot measurements may not necessarily reflect true differences of circadian-light penetration on these building facades. It is worth noting, however, that the reeds on the west façade increased the amount of daylight contribution in the window cubicles because, as observed during the site visits, the shades were not usually drawn on this façade.

A recent report by Rea and Figueiro (2013) aimed at estimating a working threshold for nocturnal melatonin suppression, suggests that one-hour light exposures of CS values less than 0.1 may be insufficient to stimulate the human circadian system. In general, the values in Table 1 are well above this value for both window and interior cubicles, for all four orientations, and for both seasons.

**Table 1. Average CS and photopic lux spot measurements performed in late spring and in winter months.**

| **Spot Measurements** | | | | |
|---|---|---|---|---|
| | **Late Spring** | | **Winter** | |
| | **CS** | **lux** | **CS** | **lux** |
| **DESKSPACE** | | | | |
| Window | 0.45 | 865 | 0.39 | 678 |
| Interior | 0.29 | 344 | 0.32 | 335 |
| **ORIENTATION** | | | | |
| East | 0.36 | 675 | 0.36 | 456 |
| North | 0.49 | 1001 | 0.34 | 393 |
| South | 0.29 | 302 | 0.40 | 766 |
| West | 0.32 | 413 | 0.35 | 412 |
| **FLOOR** | | | | |
| 4th | 0.33 | 415 | 0.31 | 379 |
| 12th | 0.34 | 487 | 0.41 | 571 |
| 17th | 0.43 | 896 | 0.37 | 570 |

### 3.2 Daysimeter Data Analyses

Table 2 shows the average individual CS light exposures obtained from the pendant Daysimeter. There was a statistically significant difference in CS values between late spring and winter for all three groupings, waking hours, work hours and after-work hours. Based upon a criterion CS of 0.1, the amount of light that participants were exposed during work hours was above the threshold for activation, suggesting that this building provides workers with enough circadian light stimulation for entrainment while the building is occupied, even in winter when the CS values were significantly lower than during the late spring months.

It is also interesting to note that the one-time spot spectroradiometric measurement may not be representative of actual circadian light exposures in the workplace. The photometric measurements in Table 1 suggest that most of the spaces in the building provide a CS value of 0.3, but the personal light exposures experienced by those wearing the Daysimeter were consistently lower.

**Table 2. Average personal CS values experienced by workers during their waking hours, at work and after work.**

| **Personal Exposures** | | | |
|---|---|---|---|
| | **Late Spring CS** | **Winter CS** | **Significance** |
| **Waking hours** | 0.26 | 0.15 | p<0.001 |
| **Work hours** | 0.28 | 0.19 | p<0.01 |
| **After work hours** | 0.22 | 0.06 | p<0.001 |

Figure 3 shows the average activity (AI) and light exposure (CS) in late spring and winter for the 15 subjects who wore the Daysimeter. Activity levels are consistently high during the waking hours. CS values tend to be highest during the middle of the day, particularly in the winter. These data also show that during late spring people spend time outdoors in the early evening. In general though, participants are exposed to much higher CS values at work than at home when they are active during the early morning and during the late evening.

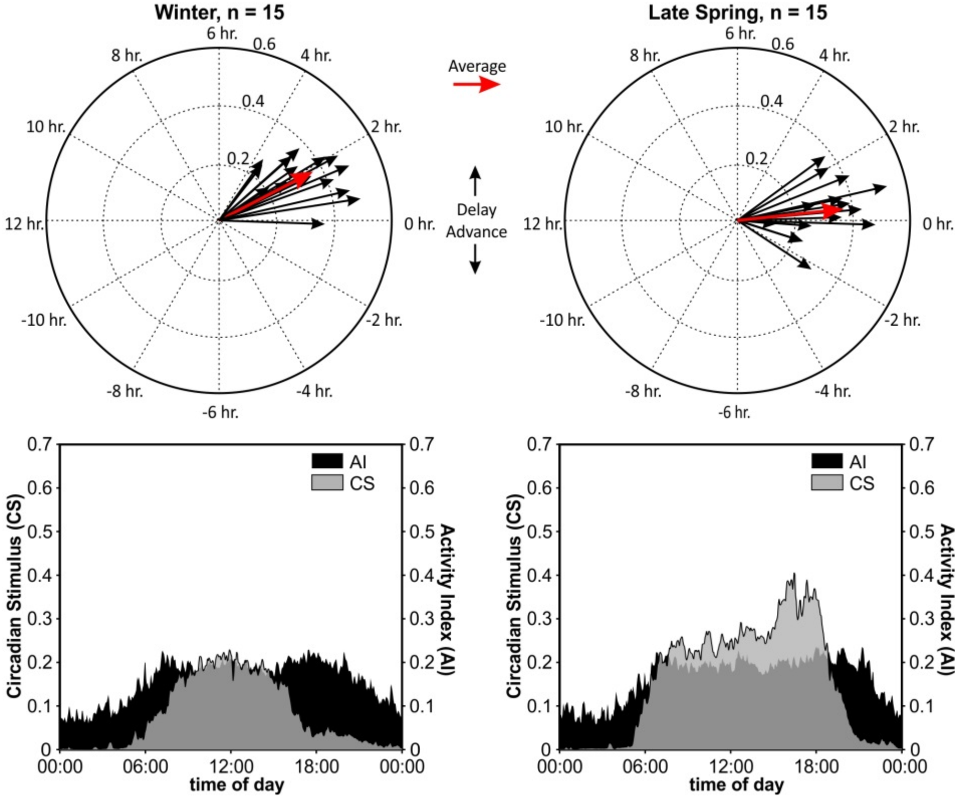

**Figure 3. Phasor distributions (upper panels), and average activity (AI) and light exposures (CS) over 24 hours (lower panels) for winter (left panels) and late spring (right panels).**

Figure 3 also shows the results of the phasor analyses. Phasor magnitudes were somewhat lower (mean = 0.35 in late spring and 0.37 in winter) than those exhibited by other groups of workers (school teachers, mean = 0.52, Rea et al., 2011; dayshift nurses, mean = 0.46, Miller et al., 2010). They were, however, very similar to those obtained in a previous study of office workers (mean = 0.37 in late spring and 0.35 in winter; Figueiro and Rea, 2014).

Phasor angles averaged 0.27 in late spring and 1.93 in winter. Positive phasor angles are common for daytime workers who remain active after the sun goes down. The mean phasor angles for school teachers (Rea et al., 2011) and dayshift nurses (Miller et al., 2010) were 0.94 and 0.68, respectively. In the earlier study of office workers by Figueiro and Rea (2014), phasor angles in the late spring and winter were similar to those presented here (mean = 0.51 in late spring and 1.1 in winter). It is worth noting that phasor angles are greater during the winter than during the late spring in both studies because activity continues longer after sunset in winter than in late spring. One more interesting observation from the present study and the previous study of office workers is that phasor angles tend to be more diverse in late spring than in winter months. We hypothesize that this is because readily available daylight after work hours during late spring supports individual differences in their preferred angle of circadian entrainment, whereas in winter the entraining light is only available during working hours.

Based on the actigraphy data from the Daysimeter, the average sleep amount in this group of workers was generally low in both late spring and winter months (average of approximately 5.9 hours per night in late spring and 6.1 hours per night in winter). Sleep efficiency was also low, around 78% in the late spring and 79% in the winter months. There were no significant differences between sleep parameters in winter and late spring months.

### 3.3 Self-reports Analyses

Sleep scores from self-reports were mixed. One scale (PSQI) suggests that over half of the participants had sleep disturbances, while the PROMIS Global Score suggests that only two participants had moderate sleep disturbances. When comparing the self-reports for late spring and winter, the PSQI scores suggest that 8 out of 18 subjects increased their sleep disturbances in winter compared to late spring months. The PROMIS Global Score suggests that 10 subjects increased their sleep disturbances in winter compared to late spring months.

Depression scores were high for two participants during both winter and late spring. The depression score increased in winter for one subject while it remained very similar for the other one. The CS values experienced by these two subjects during both seasons were not among the lowest and their phasor magnitudes were not the shortest either, suggesting that circadian disruption was not a reason for the depression exhibited by these subjects. It is possible the life events of the two participants who reported feeling depressed are more likely affecting their score than their lighting. The same two participants who reported feeling depressed also reported high negative scores and low positive scores in the PANAS. Depression scores increased in 8 out of 18 subjects from late spring to winter months. No significant differences between seasons were observed in self-report scores. KSS score (sleepiness) during the noon hour (i.e., while subjects were at work) was slightly but not significantly higher in winter than in late spring months (3.5 in late spring and 3.9 in winter).

## 4 Conclusion

The present study is one of the few studies of its kind that measured personal light exposures in a building that was designed to maximize daylighting penetration in the space. The present results underscore the importance of measuring personal light exposures to determine the actual circadian stimulation received by an occupant in a building, rather than relying on spot measurements or software simulations to determine the circadian stimulation potential of a site.

Actual personal light exposures showed that the workers were experiencing much lower circadian light than that measured using a spectroradiometer. The present study further demonstrates how occupant behaviour and furniture placement can determine whether or not daylight will be available in the space. As shown before, people will pull the shades to limit sunlight from workspaces. Therefore, it is important that building managers understand that people may not be exposed to circadian-effective light in what appears to be a building with daylight. Architects and interior designers as well as office managers need to share information to ensure workers can, in fact, have access to daylight (without increasing discomfort), to help assure greater circadian entrainment. For example, the reeds built on the west façade helped maximize daylight exposure in the space because occupants were less likely to occlude direct sunlight by pulling down the shades. Finally, even though daylight is an ideal light source for the circadian system, architects and lighting designers should always consider how to effectively use electric lighting to supplement daylight and assure that every worker is exposed to enough circadian-effective light, particularly in the morning. The Lighting Research Center (LRC) developed, using the mathematical model by Rea et al. (2012), a CS calculator to determine CS for any combination of source type and light level in photopic lux. The calculator is available at the LRC website (www.lrc.rpi.edu/resources/CircadianStimulusCalculator_May2015.xlsx). This tool will help designers select light sources and targeted photopic light levels that will increase the potential for circadian light exposure in a building. While there is still much to learn about how the built environment affects people's health and wellbeing, enough is known about how light affects the circadian system and this knowledge can help architects and designers design lighting to promote circadian entrainment, and hopefully, improve health and wellbeing in the general population.

Strengths of the present study include the within-subjects nature of the study and the use of personal, calibrated light sensors to characterize personal circadian light exposures for those working in a building designed to maximize daylight. Some limitations of the data set include: (i) A control building with limited daylight availability was not available, so the impact of daylighting in buildings on circadian system regulation may be greater than is apparent from these results alone. (ii) Research questions remain as to whether the human circadian system adapts to different environmental light levels such as a CS value at or below 0.1 and whether an 8-hour exposure to a lower CS value is sufficient for circadian entrainment. (iii) Caffeine intake was not controlled and may have affected the results, particularly if workers increased intake during the winter months to maintain alertness. (iv) Finally, it is not known whether the subjects in the present study, conducted in Northwest region of the United States, are different than those who reside in, say, the Southern region of the United States where warm, daylit days are available throughout the year.

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## 6 References

ÅKERSTEDT, T. & GILLBERG, M. 1990. Subjective and objective sleepiness in the active individual. *Int J Neurosci,* 52, 29-37.

ARENDT, J. 1995. *Melatonin and the Mammalian Pineal Gland.* London, UK: Chapman & Hall.

BOYCE, P. R. 2004. *Reviews of Technical Reports on Daylight and Productivity*. Lighting Research Center, Rensselaer Polytechnic Institute.

BOYCE, P. R., HUNTER, C. & HOWLETT, O. 2003. *The Benefits of Daylight through Windows*. Lighting Research Center, Rensselaer Polytechnic Institute.

BOYCE, P. R. & REA, M. S. 2001. *Lighting and human performance II: Beyond visibility models toward a unified human factors approach to performance.* Palo Alto, CA: EPRI.

BRAINARD, G. C., HANIFIN, J. P., GREESON, J. M., et al. 2001. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *J Neurosci,* 21, 6405.

BUYSSE, D. J., REYNOLDS, C. F., MONK, T. H., et al. 1989. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Res,* 28, 193.

CELLA, D., RILEY, W., STONE, A., et al. 2010. The Patient-Reported Outcomes Measurement Information System (PROMIS) developed and tested its first wave of adult self-reported health outcome item banks: 2005–2008. *J Clin Epidemiol,* 63, 1179-1194.

CUTTLE, C. 1983. People and windows in workplaces. People and Physical Environment Research Conference, Wellington, New Zealand.

FIGUEIRO, M. G., HAMNER, R., BIERMAN, A. & REA, M. S. 2013. Comparisons of three practical field devices used to measure personal light exposures and activity levels. *Light Res Technol,* 45, 421-434.

FIGUEIRO, M. G. & REA, M. S. 2014. Office lighting and personal light exposures in two seasons: Impact on sleep and mood. *Light Res Technol.* [epub ahead of print]

HEERWAGEN, J. & HEERWAGEN, D. 1986. Lighting and psychological comfort. *LD+A,* 6, 47-51.

HESCHONG MAHONE GROUP 1999. Daylighting in schools: An investigation into the relationship between daylighting and human performance. Pacific Gas and Electric.

HESCHONG MAHONE GROUP 2003a. Windows and classrooms: A study of student performance and the indoor environment. California Energy Commission.

HESCHONG MAHONE GROUP 2003b. Windows and offices: A study of office worker performance and the indoor environment. California Energy Commission.

HOPKINSON, R. G. 1969. *The Lighting of Buildings.* New York: Frederick A. Praeger.

JEWETT, M. E., RIMMER, D. W., DUFFY, J. F., et al. 1997. Human circadian pacemaker is sensitive to light throughout subjective day without evidence of transients. *Am J Physiol,* 273, 1800-1809.

KLEIN, D. 1993. The mammalian melatonin rhythm-generating system *In:* WETTERBERG, L. (ed.) *Light and Biological Rhythms in Man.* Oxford: Pergamon Press.

LENNIE, P., POKORNY, J. & SMITH, V. C. 1993. Luminance. *J Opt Soc Am,* 10, 1283-1293.

LEWY, A., KERN, H., ROSENTHAL, N. & WEHR, T. 1982. Bright artificial light treatment of a manic-depressive patient with seasonal mood cycle. *Am J Psychiatry,* 139, 1496-1498.

MILLER, D., FIGUEIRO, M. G., BIERMAN, A., SCHERNHAMMER, E., et al. 2010. Ecological measurements of light exposure, activity and circadian disruption. *Light Res Technol*, 42.

MOORE, R. Y. 1997. Circadian Rhythms: basic neurobiology and clinical applications. *Annu Rev Med,* 48, 253-266.

RADLOFF, L. S. 1977. The CES-D Scale: A self-report depression scale for research in the general population. *Appl Psych Meas,* 1, 385-401.

REA, M. S., BIERMAN, A., FIGUEIRO, M. G. & BULLOUGH, J. 2008. A new approach to understanding the impact of circadian disruption on human health. *J Circadian Rhythms,* 6, 7.

REA, M. S., BRONS, J. A. & FIGUEIRO, M. G. 2011. Measurements of light at night (LAN) for a sample of female school teachers. *Chronobiol Int*, 28, 673-680.

REA, M. S., FIGUEIRO, M. G., BIERMAN, A. & BULLOUGH, J. D. 2010. Circadian light. *J Circadian Rhythms,* 8, 2.

REA, M. S., FIGUEIRO, M. G., BIERMAN, A. & HAMNER, R. 2012. Modelling the spectral sensitivity of the human circadian system. *Light Res Technol,* 44, 386-396.

REA, M. S., FIGUEIRO, M. G., BULLOUGH, J. D. & BIERMAN, A. 2005. A model of phototransduction by the human circadian system. *Brain Res Rev,* 50, 213-228.

REA, M. S. & FIGUEIRO, M. G. 2013. A Working Threshold for Acute Nocturnal Melatonin Suppression from “White” Light Sources used in Architectural Applications. *J Carcinogen Mutagen*, 4.

THAPAN, K., ARENDT, J. & SKENE, D. J. 2001. An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. *J Physiol,* 535.

TUREK, F. W. & ZEE, P. C. 1999. *Regulation of Sleep and Circadian Rhythms,* New York: Marcel Dekker.

VAN SOMEREN, E. J. W., KESSLER, A., MIRMIRANN, M. & SWAAB, D. F. 1997. Indirect bright light improves circadian rest-activity rhythm disturbances in demented patients. *Biol Psychiatry,* 41, 955-963.

WATSON, D., CLARK, L. A. & TELLEGEN, A. 1988. Development and validation of brief measures of positive and negative affect: PANAS scale. *J Pers Soc Psychol,* 54, 1063.