

**TECHNICAL REPORT:  
INCREASING CIRCADIAN LIGHT EXPOSURE  
IN OFFICE SPACES**

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## TECHNICAL REPORT

### BACKGROUND

Light can have at least 2 effects on humans. First, it synchronizes or *entrains* the biological clock to the local time on Earth. Second, light elicits an acute alerting effect from people that, similar to the effect of a cup of coffee, can help a person feel less sleepy, improve reaction times, and reduce attention lapses on certain tasks. The Lighting Research Center at Rensselaer Polytechnic Institute (LRC) developed a metric, circadian stimulus (CS), which is related to the type of light (i.e., its spectrum) and the amount of light needed to affect the human circadian system, as measured by acute melatonin suppression. CS is a measure of the *effectiveness* of the retinal light stimulus for the human circadian system from threshold (CS = 0.1) to saturation (CS = 0.7). Studies have linked this metric to better circadian synchronization or *entrainment* as well as greater subjective and objective alertness in people.<sup>1,2</sup> The human circadian clock, in the absence of any external cues, free-runs with a period that is slightly greater than 24 hours (averaging 24.2 hours). Morning light advances the timing of the biological clock, resulting in earlier bedtimes and earlier morning wake times. Late afternoon/evening light, conversely, delays the timing of the biological clock, resulting in later bedtimes and later morning wake times. Although light in the middle of the day has some effect on the timing of the biological clock, that effect is attenuated compared to light received at other times of day.

Given that the biological clock's period is longer than the solar day, humans require exposure to morning light (high CS) for maintaining proper entrainment with the local time on Earth. Lack of entrainment, resulting from insufficient exposure to morning CS or excessively high CS in the evening or night, can lead to poor sleep, higher depression rates, higher stress, and other maladies. In the laboratory, the CS metric has been used to predict melatonin suppression from self-luminous devices,<sup>3</sup> and in the field, it has been used to predict entrainment in nuclear submariners<sup>4</sup> as well as sleep quality and mood in office workers<sup>5</sup> and persons with Alzheimer's disease living in senior facilities.<sup>6</sup> In these studies, entrainment was operationally defined in many ways, such as better and longer sleep at night, reduced sleep onset latency, lower sleep disturbances scores, and higher melatonin levels at night.

In addition to promoting entrainment, light can also elicit an acute, immediate alerting effect from people at any time of day or night. Earlier studies have demonstrated that the acute alerting effect of light was related to light's ability to suppress the hormone melatonin at night. It is now known that high levels of white light as well as low levels of short-wavelength light, both delivering high CS, are effective for increasing alertness at night as well as during the day, when melatonin levels are low, suggesting that other mechanisms are important for alertness in addition to melatonin suppression.<sup>1,2,5,7</sup> The LRC has demonstrated in a series of laboratory studies<sup>8,9</sup> that alertness can also be elicited by exposure to long-wavelength (red) light, which delivers very low levels of CS and is very effective for promoting alertness during the post-lunch dip. Red light at the same photopic lux at the eye was just as effective as a 470-nm (blue) light at eliciting alertness. (As the CS metric is based on the spectral sensitivity of melatonin suppression, which is maximally sensitive to short-wavelength [blue] light and minimally sensitive to longer wavelength red light, the amount of CS provided by red light is low. In other words, red light is less effective than blue light for suppressing nocturnal melatonin levels while nonetheless having an alerting effect.) In these studies, alertness was operationally

defined in terms of reaction times, electroencephalogram measurements, and self-reported scores for the Karolinska Sleepiness Scale (KSS)<sup>10</sup> and Subjective Vitality Scale (SVS)<sup>11</sup> measures.

The U.S. General Services Administration (GSA) and the LRC have completed 3 field studies in 9 federal office buildings. In the first field study, the LRC and GSA investigated the relationship between exposure to morning (8:00 a.m. to 12:00 p.m.) and all-day (8:00 a.m. to 5:00 p.m.) circadian-effective light ( $CS \geq 0.3$ ) and its effect on office workers' sleep and mood in 5 federal office buildings (Grand Junction, CO, Portland, OR, Seattle, WA, and 2 in Washington, DC).<sup>5</sup> Originally, we hypothesized that buildings with more daylight availability would deliver higher CS to workers. One of the main lessons learned from that study was that workers' behavior, combined with architectural and interior design features, occluded and reduced daylight penetration in many spaces. Since not all of the spaces in these buildings had access to daylight, supplemental electric lighting solutions would be needed to achieve the desired CS.

The second phase of this research tested a couple of electric lighting solutions that were designed to enhance CS at individual workstations with limited access to daylight. The study's second phase was conducted in 2 federal office buildings (in White River Junction, VT, and McLean, VA)<sup>12</sup> and in 2 U.S. embassies (in Reykjavik, Iceland, and Riga, Latvia) in geographic locations with limited daylight during the winter.<sup>13</sup> The LRC team developed and installed desktop luminaires designed to deliver a  $CS \geq 0.3$ . The scope of this second phase was smaller than the first, and focused on whether the lighting intervention could increase the alertness and vitality of office workers during the day while at work. A total of 36 workers from the 2 U.S. office buildings participated in the study during the summer, with 26 workers repeating the study in the fall. In the 2 embassies, which are located in higher latitudes (Reykjavik at 64.1° N, Riga at 56.9° N), a total of 32 workers participated during the winter only.

The Phase 1 results showed that compared to office workers who received low levels of circadian-effective light ( $CS \leq 0.15$ ) in the morning (i.e., before 12:00 p.m.), those who received high levels ( $CS \geq 0.3$ ) in the morning fell asleep faster at night (especially in winter), experienced better sleep quality, and had overall lower levels of depression. High levels of circadian-effective light received during the entire workday (i.e., 8:00 a.m. to 5:00 p.m.) were also associated with reduced depression and increased sleep quality.<sup>5</sup> Initially, these studies focused on determining whether daylight would deliver the desired CS to office workers, but the results suggested that, as currently designed and implemented in the 5 buildings, daylight alone was insufficient and that electric lighting was required to achieve the desired CS at the workers' eyes. The Phase 2 results showed that self-reported measures of daytime sleep and the self-reported measures of daytime vitality, alertness, and energy increased with the lighting intervention.

## **GOAL OF THE PRESENT STUDY**

The goal of this follow-up research was to evaluate whether a lighting intervention designed to deliver morning CS to promote entrainment and afternoon red light to promote alertness would increase nighttime sleep quality (the focus of Phase 1) and daytime alertness (the focus of Phase 2) in participants recruited from 3 U.S. Department of State (DOS) facilities. It was hypothesized that a  $CS \geq 0.3$  during the morning hours would provide sufficient circadian stimulation to promote entrainment and alertness while red light would promote afternoon alertness. Unlike the previous study, which ran

for 3 consecutive days, the current study ran during 3 consecutive weeks. It is known from the literature that it takes a few days for circadian phase shifting to occur. Also unlike the previous studies, red light, which has low CS, was used to promote alertness during the afternoon. The reason for using low CS in the afternoon was because high CS in the late afternoon may induce a phase delay and, to maintain entrainment, humans need to phase advance (or receive greater CS exposure in the morning than in the evening). Specifically, the research addressed 3 primary hypotheses:

1. Morning blue light ( $CS \geq 0.3$ ) will phase advance the clock and promote circadian entrainment. Because humans have a biological clock that runs with a period slightly greater than 24 hours, we need morning light to advance the clock and promote entrainment; participants will go to bed earlier and their sleep onset latency (i.e., the length of time that elapses between wakefulness before bed and sleep) will be reduced.
2. Morning blue light ( $CS \geq 0.3$ ) will elicit an acute alerting effect from participants, reducing subjective sleepiness and increasing subjective vitality/energy scores at noon.
3. Afternoon red light will elicit an acute alerting effect from participants, reducing subjective sleepiness and increasing subjective vitality/energy scores in the afternoon, especially at 3:00 p.m., close to the time of the post-lunch dip.<sup>14,15</sup> The saturated red light intervention was selected for the afternoon to provide an alerting stimulus while avoiding excessive CS exposure in the latter part of the day, thereby preventing the delay of circadian phase.

## METHODOLOGY

### PARTICIPANT RECRUITMENT

The DOS agreed to participate in this study and recruited workers from 3 of their facilities: the Harry S. Truman Building (HST), Building SA-1 (SA-1), and Building SA-17 (SA-17), all located in Washington, D.C. (Table 1). LRC and GSA personnel conducted an informational session at DOS to recruit study participants. There were no exclusion criteria for participation. Interested volunteers were enrolled in the study by the DOS immediately after the information session. Twenty participants were enrolled, but one of them (#610 at SA-1) has been excluded from the study’s results pending confirmation of compliance with the intervention.

**Table 1. Summary of Demographic Data for Participants in this Study, by Site.**

Site	Age (years) <sup>a</sup>	Gender		Total
		Male (n)	Female (n)	
Harry S. Truman Building	44.8 ± 14.5	5	11	16
U.S. Department Of State Building SA-1	57.5 ± 2.1	1	1	2
U.S. Department Of State Building SA-17	50.0 ± 7.0	1	1	2
All sites	46.7 ± 13.5	7	13	20

Note: <sup>a</sup> Mean ± standard deviation (SD).

After enrollment, LRC, GSA, and DOS staff visited each of the volunteer participants to install the lighting intervention on their desks and deliver a package containing a

Daysimeter, an actigraph, and 5 questionnaires. An LRC researcher explained the protocol again, obtained consent forms, and answered any questions. One employee from each location served as the on-site point of contact, and they collected the sealed package containing the study materials from the participants at the end of the study.

Data were collected from 2 participant cohorts over 2 separate 3-week sessions, the first occurring from September 25, 2017, to October 13, 2017, and the second occurring from October 16, 2017, to November 3, 2017. Of the 20 participants in the study, 16 participants (11 females) volunteered from the HST site, 2 (1 female) volunteered from the SA-1 site, and 2 (1 female) volunteered from the SA-17 site (Table 1).

## MEASUREMENT PROCEDURES

### **DEVICES**

The [Daysimeter](#), a calibrated light-measuring device and activity monitor developed by the LRC,<sup>16</sup> was used to collect personal light and activity data from the participants. The Daysimeter is calibrated in terms of both orthodox photopic illuminance (lux) and circadian illuminance ( $CL_A$ ).  $CL_A$  calibration is based upon how the human circadian system responds to light. From the recorded  $CL_A$  values, it is then possible to determine the magnitude of CS, which is a measure of a light source's effectiveness for stimulating the circadian system as measured by its ability to acutely suppress the body's production of melatonin.<sup>17,18</sup> Participants wore the Daysimeter from when they woke up in the morning until they went to bed at night to measure their CS exposure during waking hours. Participants were asked to remove the Daysimeter when going to bed, and it is not known whether they performed activities such as using self-luminous displays before falling asleep. It should be noted, however, that we assumed that the participants would not substantially change their behavior before bed from week to week, so this was hypothesized to be constant during the study period.

Participant's rest-activity patterns were measured via actigraphy (Philips Actiwatch Spectrum Plus, Philips Respironics, Bend OR), which was recorded 24-hours/day during Weeks 1 and 3 of the study, excluding weekends (see Protocol, below). The Actiwatch, worn in the wrist, is equipped with a highly sensitive accelerometer that measures users' activity or lack thereof, and records when (and for how long) the device has been removed.

Using data from the actigraphy and the software developed by the device's manufacturer, the following sleep measures were obtained: (1) sleep start time (time of day); (2) sleep end time (time of day); (3) sleep onset latency, or the length of time that elapses between wakefulness before bedtime and sleep (in minutes); (4) sleep efficiency, or the proportion of time spent in bed while actually asleep (percentage); (5) sleep time, or the time that elapses between falling sleep and waking up (in minutes); and (6) wake time, or the amount of time momentarily spent awake after falling asleep and waking up for the next day (in minutes).

Sleep start time was calculated using the participants' event diary (time to bed and time to wake) and the actigraph's detection of low activity and low light levels for durations that are > 3 hours. After this period was defined, the proprietary software automatically detected the time spent asleep within the rest period.

Sleep end time was calculated using the participants' event diary (time to bed and time to wake) and 2 actigraphy measures: increases in activity level (indicated on the actogram's solid wake bar) and increases in light level above  $1.0 \mu\text{W}/\text{cm}^2$ . The light level in this case

was recorded by the actigraph under the assumption that, because participants would be wearing the device during sleep, light levels would be low while they were in bed.

Sleep onset latency is the time required to fall asleep after initiating the intent to sleep. In other words, it is the elapsed time between the start of a given rest interval and the sleep interval start time.

Sleep efficiency is indicated by the percentage of time spent in bed sleeping. It is based on total sleep time divided by interval duration minus total invalid time (sleep-wake) of the given rest interval multiplied by 100.

Sleep time is calculated from the total number of epochs for the given interval scored as sleep by the Actiware software, multiplied by the epoch length.

Wake time is the total number of epochs between the start time and end time of a given interval scored as awake by the Actiware software.

The actigraph data were also used to calculate interdaily stability (IS) and intradaily variability (IV).<sup>19</sup> The IS ratio quantifies the extent to which all recorded 24-hour activity profiles resemble each other, which represents the day-by-day regularity of the sleep-wake pattern. Higher IS ratios indicate better interdaily stability. The IV ratio quantifies the fragmentation of the rhythm, or the frequency and extent of transitions between periods of rest and activity. Lower IV ratios indicate better intradaily variability.

Finally, the actigraph data were used to calculate activity acrophase (i.e., the tendency of the peak of the activity rhythm), which is the phase angle of a cosine fit to the actigraph activity data using the method of least squares.<sup>20</sup> This measure reports results as the time of day at which activity was at its maximum. Activity acrophase is a measure of circadian phase (or circadian timing). An earlier acrophase suggests a phase advance of the circadian clock because peak activity occurred earlier in the day. In the present study, given that the participants were receiving high CS in the morning, at a time when light advances the circadian clock, we expected their acrophase to occur earlier in the day after the intervention.

## **QUESTIONNAIRES**

Participants completed a series of questionnaires inquiring about sleep habits (Pittsburgh Sleep Quality Index [PSQI] and Karolinska Sleepiness Scale [KSS]) and subjective feelings of stress (Perceived Stress Scale [PSS-10]), depression (Center for Epidemiologic Studies Depression Scale [CES-D]), and vitality and alertness (Subjective Vitality Scale [SVS]). The schedule for participants' completion of the questionnaires can be found in Protocol, below. These questionnaires were selected because they have been used to probe participants' subjective sleepiness, vitality, and energy levels in previous studies.

The PSQI questionnaire<sup>21</sup> is a subjective measure of sleep quality and patterns experienced by participants for the majority of days and nights over the past month. It measures sleep quality from responses in 7 areas: subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbance, use of sleep medication, and daytime dysfunction. Answers are scored on a scale ranging from 0 to 3, and the questionnaire yields a single global score. A global score  $\geq 5$  indicates a poor sleeper. The PSQI questionnaire was completed once at the beginning of the baseline week and once again at the end of the study.

The KSS questionnaire<sup>10</sup> is a subjective measure of sleepiness that assesses participants' present state on a 9-point scale ranging from 1 ("extremely alert") to 9 ("very sleepy, great effort to keep awake, fighting sleep"). The KSS questionnaire was completed 4 times per day (upon arrival and at 12:00 p.m., 3:00 p.m., and departure) on each day of the baseline week and the second intervention week (Week 3).

The CES-D questionnaire<sup>22</sup> is designed to measure depressive symptoms. This 20-item test measure asks how often over the past week participants experienced symptoms associated with depression, such as restless sleep, poor appetite, and feelings of loneliness. 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). Total scores range from 0 to 60, with scores > 16 indicating greater depressive symptoms. The CES-D questionnaire was completed once at the beginning of the baseline week and once again at the end of the study.

The PSS-10 questionnaire<sup>23</sup> assesses participants' thoughts and feelings over the past month by posing 10 questions concerning how often they have thought or felt a specific way. Answers are scored on a 5-point scale ranging from 0 (never) to 4 (almost always). Total scores  $\geq 20$  are considered to indicate high stress. The PSS-10 questionnaire was completed once at the beginning of the baseline week and once again at the end of the study.

The SVS questionnaire<sup>11</sup> assesses participants' perceptions of feeling alive, vital, energetic or energized, alert, awake, and optimistic "at the present time." Participants' responses to 7 individual statements were scored on a 7-point scale ranging from 1 (not at all true) to 7 (very true). The SVS questionnaire was completed 4 times per day (upon arrival and at 12:00 p.m., 3:00 p.m., and departure) on each day of the baseline week and the second intervention week (Week 3).

## LIGHTING INTERVENTION

### **DESKTOP LUMINAIRES**

The LRC developed and built 20 plug-in LED luminaires for mounting on desktops near participants' computer monitors. The luminaires were designed to deliver saturated blue light in the morning (6:00 a.m. to 12:00 p.m.), white light at midday (12:00 p.m. to 1:30 p.m.), and saturated red light in the afternoon (1:30 p.m. to 5:00 p.m.) (Figure 1). Transitions between each of the lighting modes were accomplished in 1 minute. The luminaire automatically turned off at 5:00 p.m. and remained off until 6:00 a.m. the next day. The specifications for the 3 lighting interventions are shown in Tables 2 and 3, and their spectral power distributions are shown in Figure 2.



**Figure 1. The luminaire designed for the study, showing its 3 lighting modes.**

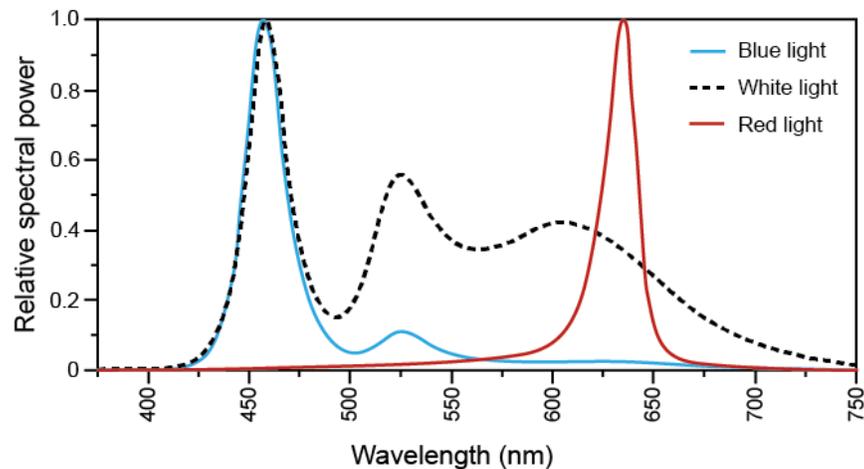
**Table 2. Schedule and specifications for the lighting interventions used in this study. Note that for the white light intervention, a higher light level was required to achieve the criterion CS value  $\geq 0.3$  compared to the saturated blue light intervention.**

Time of Day	Lighting Intervention	$\lambda_{\max}$ (nm)	$E_v$ (lux)	CS
6:00 a.m. to 12:00 p.m.	blue	455	50	0.40
12:00–1:30 p.m.	white (6500 K)	n/a	200	0.30
1:30–5:00 p.m.	red	634	50	0

**Table 3. Calculations of the five  $\alpha$ -opic irradiances<sup>a</sup> and equivalent melanopic lux for the 3 lighting interventions, following the SI-compliant approach recommended by the International Commission on Illumination (CIE).**

Lighting intervention	Cyanopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Melanopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Rhodopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Chloropic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Erythropic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Equivalent melanopic lux (EML)
Blue	22.38	22.99	20.76	14.03	10.16	191
White	14.50	24.15	28.57	32.11	33.81	201
Red	0.37	0.93	1.46	4.05	10.22	8

*Note:* (a) Based upon the spectral irradiance distributions of the light sources,  $\alpha$ -opic irradiances are calculated using the CIE TN 003:2015 proposed SI-complaint version of the Lucas et al. <sup>24</sup> toolbox, which is available as a freely downloadable electronic document ([http://files.cie.co.at/784\\_TN003\\_Toolbox.xls](http://files.cie.co.at/784_TN003_Toolbox.xls)).

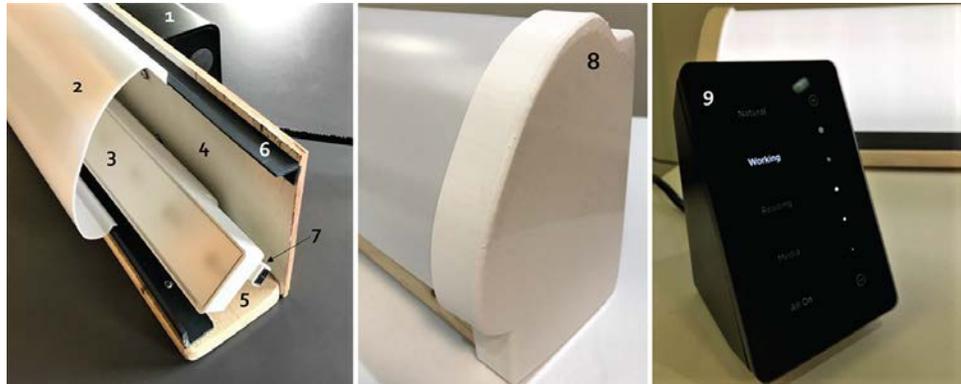


**Figure 2. Spectral power distribution of the desktop luminaire’s 3 modes.**

The saturated blue lighting intervention was selected for the morning to provide high CS and promote alertness and circadian entrainment. The morning blue light was expected to advance sleep times because morning blue light advances circadian phase. Given that the human circadian system free runs with a period slightly greater than 24 hours, morning blue light advances the clock and promotes entrainment (see Background, above). The 6500 K white light intervention was selected for midday to provide a smooth transition from the blue to the red light, while still delivering a CS  $\geq 0.3$ . The saturated red light intervention was selected for the afternoon to provide an alerting stimulus while avoiding excessive CS exposure in the latter part of the day, thereby preventing the delay of circadian phase.

Each desktop device consisted of 2 fully tunable spectrum 12-in. linear accent luminaires (model G2, Ketra, Austin, TX) placed end to end and housed in a custom-built wooden frame. The luminaires were covered by a domed white acrylic light diffuser (Utilitech Pro Wrap shop light, Lowe's, Mooresville, NC) and enclosed with endcaps that were 3D printed (3D white PLA filament, Robo, San Diego, CA) by the LRC (Figure 3). The luminaire was driven by a satellite link controller (model N3, Ketra, Austin, TX) with a touchpad interface (model X1, Ketra, Austin, TX). The assembled desktop device measured 24 in. long  $\times$  7 in. high  $\times$  7.5 in. deep.

On September 20–21, 2017, the LRC, together with GSA and DOS staff, installed 16 luminaires at the HST site, 2 luminaires at the SR-1 site, and 2 luminaires at the SR-17 site while also performing on-site photometric assessments of each device. A single luminaire was installed on each participant's workplace desktop. As shown in Figure 3, the linear accent housed in each luminaire was mounted and directed at a 30° angle (see Figure 3, items 3 and 5) to direct the light at participants' eyes. The linear accent remained in that position for the duration of the lighting intervention.



**Figure 3. Components of the desktop luminaire: (1) satellite link controller, (2) light diffuser, (3) LED linear accent, (4) plywood housing back, (5) pine board base, (6) ½-in.  $\times$  1-in., PVC 90° angle ( $\times$ 2), (7) connector cable, (8) installed endcap, (9) touchpad interface.**

To ensure compliance with the lighting intervention, each workspace was provided with a HOBO occupancy/light data logger (model HOBO UX90-005, Onset Computer Corporation, Bourne, MA) that monitored desk occupancy and indoor light changes to identify when participants were seated in front of the desktop luminaire. The HOBO data indicates that no participants were out of compliance for the lighting intervention (Appendix 2).

### **ON-SITE PHOTOMETRIC MEASUREMENTS**

The research team performed baseline photometric measurements using an optical spectrometer (Model USB650 Red Tide Spectrometer, Ocean Optics, Winter Park, FL) or lux meter (Model BTS256-E, Gigahertz-Optik, Türkenfeld, DE). Measurements were recorded at each participant's desk, first with the desktop luminaire turned off, and then followed by a single measurement for each of the Desktop luminaire's lighting modes (totaling 4 measurements per device). All measurements were taken at the participants' eye level (Tables 4 and 5).

**Table 4. Photometric/Daysimeter measurements taken at the 3 sites.**

Participant	Lighting intervention	CS	CL <sub>A</sub>	Lux
Harry S. Truman Building (HST)				
600	none <sup>a</sup>	—	—	—
	blue	0.36	374	58
	white	0.25	210	186
	red	0.04	30	42
601	none	0.17	130	142
	blue	0.45	593	167
	white	0.32	301	361
	red	0.17	130	174
602	none	0.07	51	113
	blue	0.39	432	141
	white	0.28	244	284
	red	0.18	132	141
603	none	0.12	87	113
	blue	0.47	661	151
	white	0.39	427	399
	red	0.10	71	161
604	none	0.03	23	38
	blue	0.45	621	68
	white	0.17	124	121
	red	0.08	57	70
605	none	0.25	212	208
	blue	0.51	852	279
	white	0.42	522	568
	red	0.28	250	285
607	none	0.08	56	54
	blue	0.34	331	68
	white	0.20	155	170
	red	0.08	58	72
608	none <sup>a</sup>	—	—	—
	blue	0.34	339	36
	white	0.21	165	156
	red <sup>a</sup>	—	—	—
613	none	0.15	110	125
	blue	0.36	366	152
	white	0.27	232	234
	red	0.14	100	143
617	none	0.14	98	123
	blue	0.46	644	142
	white	0.34	337	330
	red	0.11	75	151
618 <sup>b</sup>	none	0.08	53	52
	blue	0.35	347	70
	white	0.22	178	191
	red	0.09	61	77
619	none	0.14	100	102
	blue	0.50	817	145
	white	0.38	406	357
	red	0.13	90	142

Participant	Lighting intervention	CS	CL <sub>A</sub>	Lux
622	none	0.17	127	149
	blue	0.42	501	216
	white	0.34	337	333
	red	0.17	130	218
623	none	0.11	74	153
	blue	0.43	549	211
	white	0.34	343	356
	red	0.24	192	180
Building SA-1				
624	none <sup>a</sup>	—	—	—
	blue	0.42	516	157
	white	0.33	320	355
	red	0.11	74	135
Building SA-17				
614	none <sup>a</sup>	—	—	—
	blue	0.45	621	38
	white	0.31	292	251
	red	0.01	4	53
625	none <sup>a</sup>	—	—	—
	blue	0.43	535	48
	white	0.30	269	249
	red	0.02	16	59

**Notes:** Participant 620 (HST site) joined the study after the on-site photometric assessment, so no data are available. Participant 621 (HST site) was not in the office when the research team performed the on-site photometric assessment.

(a) Data not available.

(b) This workspace had very low general illuminance.

**Table 5. Calculations of the five  $\alpha$ -opic irradiances<sup>a</sup> and equivalent melanopic lux for the photometric measurements taken at the 3 sites, following the SI-compliant approach recommended by the CIE.**

Participant	Lighting intervention	Cyanopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Melanopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Rhodopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Chloropic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Erythroptic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Equivalent melanopic lux (EML)
Harry S. Truman Building (HST)							
600	none <sup>b</sup>	—	—	—	—	—	—
	blue	18.09	16.70	16.05	12.62	10.71	139
	white	12.67	18.43	23.46	28.79	30.66	153
	red	0.83	1.85	2.69	4.68	7.69	15
601	none	4.30	8.37	12.65	19.41	23.58	70
	blue	30.86	30.95	31.78	30.19	29.96	258
	white	20.13	31.32	41.13	53.72	59.70	261
	red	4.24	8.39	12.76	21.44	30.43	70
602	none	4.42	8.12	11.55	16.03	18.71	68
	blue	22.72	24.11	25.56	24.88	24.88	201
	white	16.30	25.24	33.11	42.50	46.92	210
	red	4.55	8.45	12.12	18.26	24.51	70
603	none	6.27	9.73	13.02	16.75	18.74	81
	blue	33.41	33.64	33.72	29.48	27.37	280

Participant	Lighting intervention	Cyanopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Melanopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Rhodopic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Chloropic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Erythroptic irradiance ( $\mu\text{W}/\text{cm}^2$ )	Equivalent melanopic lux (EML)	
604	white	26.51	39.03	49.60	61.27	66.03	325	
	red	6.42	10.23	13.92	20.47	28.61	85	
	none	1.86	2.90	4.02	5.43	6.23	24	
	blue	30.59	27.09	24.68	17.37	13.63	225	
605	white	7.89	11.67	14.88	18.53	20.06	97	
	red	2.21	3.63	5.18	8.34	12.59	30	
	none	6.16	13.17	19.39	28.50	34.64	110	
	blue	43.56	44.79	47.68	47.62	49.32	373	
607	white	33.16	49.95	65.48	84.59	94.26	416	
	red	7.29	15.53	22.98	36.18	49.36	129	
	none	1.77	3.44	5.01	7.45	9.05	29	
	blue	16.92	14.81	14.67	12.90	12.35	123	
608	white	10.36	14.78	19.44	25.36	28.14	123	
	red	1.82	3.56	5.27	8.83	12.78	30	
	none <sup>b</sup>	—	—	—	—	—	—	
	blue	16.38	13.71	12.53	8.89	7.09	114	
613	white	10.42	14.67	18.93	23.77	25.55	122	
	red <sup>b</sup>	—	—	—	—	—	—	
	none	7.27	11.66	15.12	18.87	20.86	97	
	blue	20.04	22.56	25.04	25.78	26.27	188	
617	white	15.00	22.29	28.61	35.61	38.75	185	
	red	7.17	11.65	15.25	20.14	24.60	97	
	none	6.44	11.45	14.97	18.67	20.45	95	
	blue	33.06	32.46	32.58	28.09	25.60	270	
618 <sup>c</sup>	white	21.44	31.94	40.92	50.71	54.49	266	
	red	5.97	10.77	14.30	19.96	26.58	90	
	none	1.72	3.42	4.94	7.18	8.60	28	
	blue	17.88	16.67	16.35	13.86	12.80	139	
619	white	11.82	17.37	22.56	28.79	31.53	145	
	red	1.95	3.92	5.73	9.39	13.75	33	
	none	6.48	10.03	12.86	15.70	16.99	83	
	blue	41.68	38.70	37.71	30.64	26.72	322	
622	white	25.43	35.78	45.25	55.28	58.91	298	
	red	6.82	10.66	13.87	18.99	25.16	89	
	none	8.59	13.60	17.79	22.44	24.84	113	
	blue	27.17	31.21	34.81	36.36	37.27	260	
623	white	21.26	32.10	41.04	50.95	55.21	267	
	red	9.99	16.42	22.03	30.11	37.50	137	
	none	5.45	12.17	16.66	22.27	25.46	101	
	blue	28.35	31.90	34.98	35.78	36.59	265	
624	white	21.24	33.14	42.80	53.95	59.05	276	
	red	5.52	11.89	16.32	23.71	31.33	99	
	Building SA-1							
	none <sup>b</sup>	—	—	—	—	—	—	
blue	26.13	26.19	27.03	26.80	28.25	218		
white	20.49	30.90	40.24	52.58	59.02	257		
red	1.65	4.72	7.66	15.12	24.38	39		

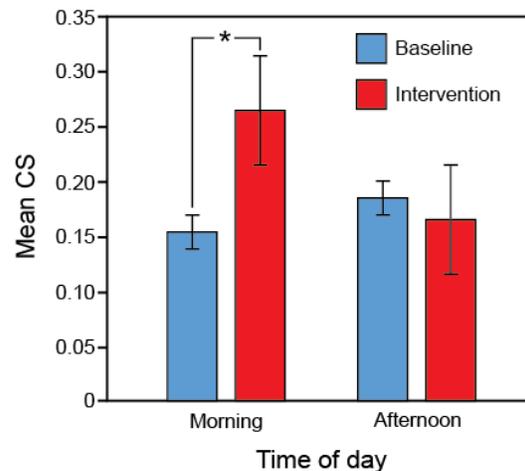


intervention schedule shown in Table 2. Participants did not wear the Daysimeters and actigraphs, and did not fill out any questionnaires, during Week 2. The reason for this was two-fold. First, as we were interested in the longer term effect of the intervention, the first week of the intervention served as an acclimation week. Second, we wanted to minimize burden on participants and thereby increase the potential for compliance. Therefore, participants were again asked to continuously wear the actigraphs and Daysimeters (similar to Week 1) and fill out the KSS and SVS questionnaires 4 times a day on Week 3 only. On the final day of Week 3, participants again filled out the PSQI, CES-D, and PSS-10 questionnaires. The participants then placed the Daysimeters, actigraphs, and completed questionnaires in sealed packages and returned them to the on-site point of contact.

## RESULTS

### CIRCADIAN STIMULUS (CS)

The mean  $\pm$  standard error of the mean (SEM) CS exposures in the morning (between 6:00 a.m. and 12:00 p.m.) and the afternoon (2:00–5:00 p.m.) were calculated (Figure 5). As expected, morning CS was significantly greater during intervention days than baseline, while afternoon CS was not. The results obtained for a participant (610 at SVA-1) who might have worn amber-filtering glasses during the experiment were excluded from this analysis. The CS values recorded during the intervention were, on average, slightly lower than the targeted CS of 0.3, possibly because participants were not seated in front of their computers at all times. (The HOB0 data indeed indicated periods during the workday when desks appeared to be vacant.) In terms of the baseline CS, the lower levels in the morning might be attributable to workers being absent from their offices at 6:00 a.m., or due to less daylight/sunlight in the spaces.



**Figure 5. Mean CS exposures experienced by the participants in the morning (6:00 a.m. to 12:00 p.m.) and afternoon (2:00–5:00 p.m.) at baseline and intervention (Week 3). The asterisk indicates statistical significance ( $p < 0.05$ )**

### QUESTIONNAIRES

For all of the questionnaire data, Day 1 scores were not included in the analyses because of Columbus Day holiday (which occurred during the cohort 2 session). Data included in the analyses were obtained from Days 2-5 for the baseline and intervention (Week 3). Seventeen participants completed the questionnaires on at least 2 of the 4 days, and their

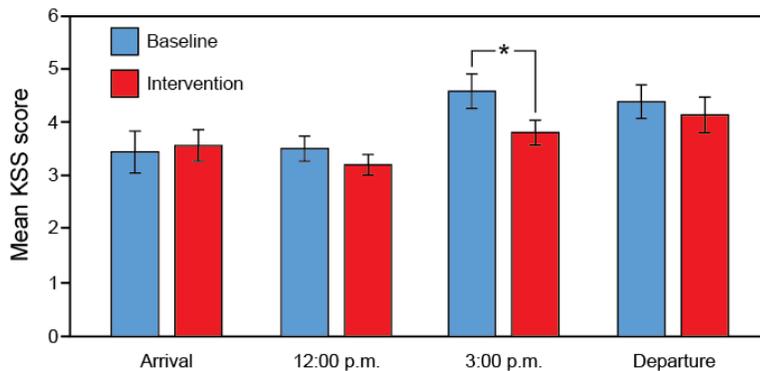
data were included in the analyses. As with the other measures, the results obtained for a participant (610 at SVA-1) who might have worn amber-filtering glasses during the experiment were excluded from these analyses.

Moreover, given that there were data missing at various time points, the data for Days 2-5 were averaged for each of the 4 times of day (arrival, 12:00 p.m., 3:00 p.m., and departure). Statistical analyses were performed on these averages.

### **KAROLINSKA SLEEPINESS SCALE (KSS)**

Figure 6 and Table 6 show the mean  $\pm$  SEM KSS scores recorded by the participants at baseline and intervention (Week 3) for the 4 times of day. Paired, two-tailed *t*-tests showed that KSS scores were significantly reduced ( $p = 0.04$ ) during the intervention week at 3:00 p.m. Although not statistically significant, sleepiness scores during the intervention were lower than during baseline at 12:00 p.m. and at departure.

For comparison, the mean  $\pm$  SEM KSS scores obtained with the lighting intervention during the Phase 2 study<sup>25</sup> were  $3.82 \pm 0.14$  upon arrival,  $3.5 \pm 0.14$  at 12:00 p.m.,  $3.88 \pm 0.15$  at 3:00 p.m., and  $3.99 \pm 0.15$  at departure, fairly consistent with the present study. In Phase 2, the lighting intervention (CS of 0.3 all day) was delivered for 2 consecutive days rather than 2 consecutive weeks.



**Figure 6. Mean  $\pm$  SEM KSS scores recorded by the participants at baseline and intervention (Week 3) by time of day. The asterisk denotes statistical significance.**

**Table 6. Mean  $\pm$  SEM KSS scores and *p* values recorded by the participants at baseline and intervention (Week 3) for the 4 times of day. Lower scores indicate less sleepiness.**

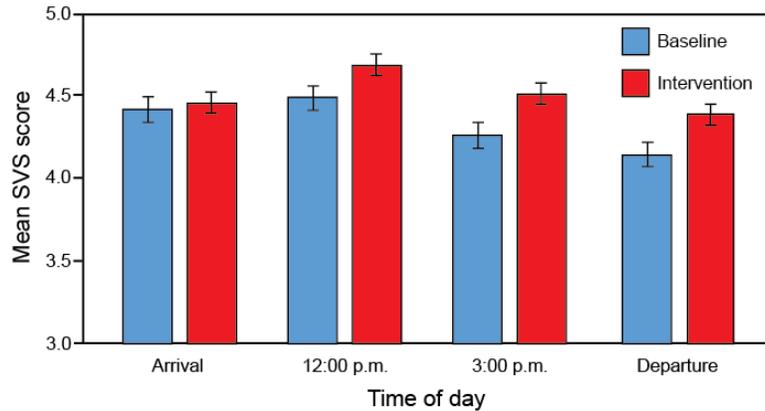
Study week	Time of day			
	Arrival	12:00 pm.	3:00 p.m.	End of day
Baseline	3.4 $\pm$ 0.22	3.5 $\pm$ 0.20	4.6 $\pm$ 0.22	4.4 $\pm$ 0.22
Intervention (Week 3)	3.6 $\pm$ 0.22	3.2 $\pm$ 0.13	3.8 $\pm$ 0.18	4.1 $\pm$ 0.22
<i>p</i> value	0.64	0.12	<b>0.04</b>	0.52

### **SUBJECTIVE VITALITY SCORES (SVS)**

Figure 7 and Table 7 show the mean  $\pm$  SEM SVS scores recorded by participants at baseline and intervention (Week 3) for the 4 times of day. There were no statistically significant differences between SVS scores at any time point.

Table 8 shows the mean  $\pm$  SEM scores for the PSQI, PSS, and CES-D measures at baseline and intervention (Week 3). No significant differences were observed for any of the questionnaire responses.

For comparison, the composite mean  $\pm$  SEM SVS scores obtained with the lighting intervention during the Phase 2 study<sup>25</sup> were  $4.24 \pm 0.12$  upon arrival,  $4.53 \pm 0.12$  at 12:00 p.m.,  $4.45 \pm 0.12$  at 3:00 p.m., and  $4.38 \pm 0.12$  at departure, also consistent with the data in the present study. In Phase 2, the lighting intervention (CS of 0.3 all day) was delivered for 2 consecutive days rather than 2 consecutive weeks.



**Figure 7. Mean  $\pm$  SEM SVS scores recorded by participants at baseline and intervention (Week 3) by the 4 times of day.**

**Table 7. Mean  $\pm$  SEM SVS scores and p values recorded by participants at baseline and intervention (Week 3) for the 4 times of day. Higher scores indicate higher alertness, vitality, and energy.**

Study week	Arrival	12:00 p.m.	3:00 p.m.	Departure
Baseline	4.41 $\pm$ 0.34	4.48 $\pm$ 0.22	4.26 $\pm$ 0.21	4.14 $\pm$ 0.20
Intervention	4.45 $\pm$ 0.26	4.68 $\pm$ 0.26	4.51 $\pm$ 0.23	4.38 $\pm$ 0.21
p value	0.88	0.26	0.17	0.23

**Table 8. Mean  $\pm$  SEM scores and p values recorded by participants for the PSQI, PSS, and CES-D measures at baseline and intervention (Week 3).**

Study week	PSQI	PSS-10	CES-D
Baseline	7.39 $\pm$ 0.81	12.89 $\pm$ 1.45	4.94 $\pm$ 0.76
Intervention	8.17 $\pm$ 1.00	12.89 $\pm$ 1.67	5.28 $\pm$ 0.80
p value	0.28	0.90	0.51

### **ACTIGRAPHY DATA – SLEEP AND ACTIVITY MEASURES**

Data from 15 participants who wore the device for at least 2 of the 4 days of each data collection period were included in the analyses. As with the other measures, the results obtained for a participant (610 at SVA-1) who might have worn amber-filtering glasses during the experiment were excluded from these analyses.

Table 9 shows the results for the sleep outcome measures. The only significant effect ( $p = 0.016$ ) was observed on sleep end times. As hypothesized, morning blue light exposures advanced the timing of participants' sleep. Participants woke up 38 minutes earlier on average and fell asleep 8 minutes earlier on average. The total sleep times, calculated by

the actigraph algorithm, however, showed a reduction of 16 minutes. Given that total sleep time takes sleep epochs during the night into account, not just the sleep onset and offset times, it appears that the intervention increased participants' sleep epochs during the night, although the time in bed was reduced because they woke up earlier.

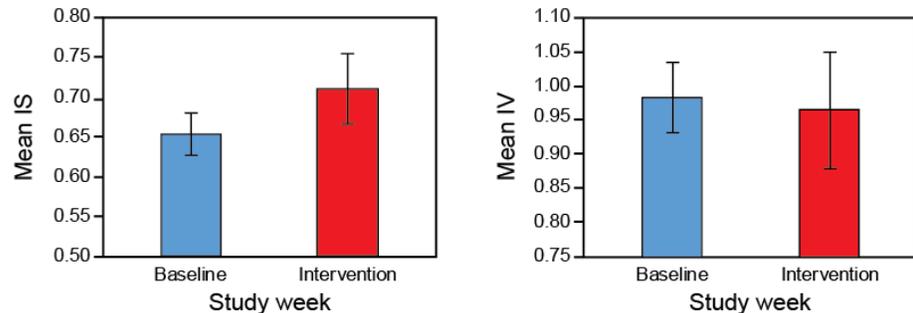
As for the activity-related measures, Table 10 and Figures 8 and 9 show the mean IS, mean IV, and activity acrophase results at baseline and intervention (Week 3). Both the IS and IV measures improved with the intervention and the activity acrophase was earlier, as expected, but the differences in values did not reach statistical significance.

**Table 9. Sleep outcome measures results at baseline and intervention (Week 3).**

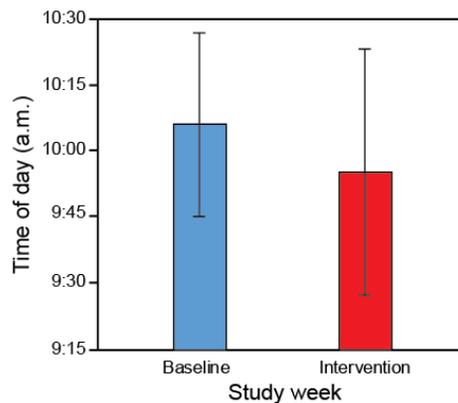
Study week/ <i>p</i> value	Sleep start time (time of day: hh:mm)	Sleep end time (time of day: hh:mm)	Sleep onset latency (min)	Sleep efficiency (%)	Wake time (min)	Sleep time (min)
Baseline	22:27	05:41	6.9	96.2	5.9	426.6
Intervention	22:19	05:19	9.1	95.4	7.2	410.3
<i>p</i> value	0.60	<b>0.016</b>	0.42	0.31	0.30	0.21

**Table 10. Activity-related measures results at baseline and intervention (Week 3).**

Study week/ <i>p</i> value	Interdaily stability (IS) (mean)	Intradaily variability (IV) (mean)	Activity acrophase (time of day, a.m.)
Baseline	0.65	0.98	10:06:02
Intervention	0.71	0.96	9:55:06
<i>p</i> value	0.22	0.82	0.77



**Figure 8. Mean IS (left) and mean IV (right) ratios recorded for participants at baseline and during the intervention (Week 3). Higher ratios indicate better IS and lower ratios indicate better IV.**



**Figure 9. Activity acrophase recorded for participants at baseline and during the intervention (Week 3). An earlier acrophase indicates a phase advance in the participant's circadian clock.**

## CONCLUSIONS

The findings observed in this study partially support our hypotheses. First, in respect to Hypothesis 1 (see Goals of the Present Study, above), high CS in the morning (delivered via 470-nm, blue light from 06:00 a.m. to 12:00 p.m.) appears to have advanced participants' circadian clock, as observed by the significantly ( $p = 0.016$ ) earlier sleep offset times (i.e., on average, participants woke up 38 minutes earlier after the intervention). An earlier acrophase, albeit not statistically significant, is also an indication of early circadian phase (see Table 10). In other words, the lighting intervention appears to have resulted in earlier bedtimes and earlier wake times, modestly promoting the participants' circadian entrainment.

Contrary to our hypothesis, however, participants' sleep start times did not significantly advance and their sleep onset latency times were not significantly reduced, although sleep start times did advance by an average of 8 minutes (see Table 9). The total sleep times, calculated by the actigraph algorithm, however, showed a reduction of 16 minutes. Given that total sleep time takes into account sleep sampling epochs during the night (i.e., summing the number of individual 60-second intervals [epochs] scored as sleep by the Actiware software), not just the sleep onset and offset times, it appears that the intervention increased the participants' sleep epochs during the night. However, participants' actual time in bed was reduced because they woke up earlier.

It should be noted, however, that although total sleep was reduced, measures of circadian rhythms consolidation (IV and IS) suggest greater rest–activity pattern consolidation (i.e., less disruption) with the intervention. The IS ratio quantifies the extent to which all recorded 24-hour activity profiles resemble each other. The resulting ratios for this measure, which essentially represent the day-by-day regularity of the sleep–wake pattern, were higher after the intervention. (A higher IS ratio indicates better interdaily stability and better entrainment). The IV ratio, which quantifies the fragmentation of the rhythm, or the frequency and extent of transitions between periods of rest and activity, was lower after the intervention. (A lower IV ratio indicates better intradaily variability and better entrainment.)

The results for acute alertness, which this study measured using the KSS and SVS metrics, partially supported our Hypotheses 2 and 3 and are consistent with the results of LRC laboratory studies. In the present study, red light exposure during the post-lunch dip (i.e., around 3:00 p.m.) significantly decreased subjective sleepiness, as observed by the lower KSS scores at this time of day. There was also a decrease in KSS scores at 12:00 p.m. and at departure, but this difference did not reach statistical significance. A similar pattern was observed in the SVS scores. The intervention increased SVS scores at 12:00 p.m., 3:00 p.m., and departure, but probably due to the small sample size, none of the differences were statistically significant. We find it interesting that the blue lighting intervention upon arrival at work did not have a significant effect on participants' KSS or SVS scores, but this is probably due to the limited exposure time that had elapsed when the questionnaires were filled out.

## CREDITS

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## APPENDIX 1: EQUIVALENT MELANOPIC LUX

The General Services Administration requested that calculations be made to estimate equivalent melanopic lux (EML) from the photometric measurements performed on site and from the Daysimeter data collected from participants. “Melanopic lux,” can be loosely described as flux density weighted not by the photopic luminous efficiency function, or  $V(\lambda)$ , peaking at 555 nm based on the response of foveal, long- and middle-wavelength sensitive cones, but by a luminous efficiency function peaking at 480 nm based on the action spectrum of melanopsin. Melanopsin is the retinal photopigment contained within our eyes’ intrinsically photosensitive retinal ganglion cells (ipRGCs), which form the main neural conduit from the retina to the brain’s master clock. It has been shown, however, that rods, cones, and ipRGCs, not just the ipRGCs, participate in how the retina converts light signals into electrical signals to the biological clock. Moreover, photometric units have not been established for this luminous efficiency function, so it should be noted that it is not possible to actually quantify light in terms of “melanopic lux.” In fact, to comply with SI units, the International Commission on Illumination (CIE) proposed that SI-compliant,  $\alpha$ -opic irradiances be calculated<sup>26,27</sup> instead of the  $\alpha$ -opic lux (non-SI compliant) as proposed by Lucas *et al.*<sup>24</sup>

Using the spectral irradiance distributions from the spectroradiometric measurements collected on site, the  $\alpha$ -opic irradiances were calculated (see Tables 3 and 5) for each experimental condition with the International Commission on Illumination’s (CIE)<sup>26,27</sup> SI-compliant version of the Lucas *et al.* melanopic illuminance toolbox.<sup>24</sup> The  $\alpha$ -opic irradiance metric refers to how each of the human photoreceptors responds to light stimulus. The  $\alpha$ -opic irradiance,  $E_{e,\alpha}$ , was determined by convolving the spectral irradiance of the light source,  $E_{e,\lambda}(\lambda)$ , for each wavelength, with the desired action spectrum,  $s_\alpha(\lambda)$ , where  $s_\alpha(\lambda)$  is normalized to one at its peak:

$$E_{e,\alpha} = \int E_{e,\lambda}(\lambda) s_\alpha(\lambda) d\lambda$$

Given that the  $\alpha$ -opic irradiance values and equivalent melanopic lux (EML) provided in Tables 3 and 5 do not refer to the predicted response by the circadian system (i.e., melatonin suppression),  $CL_A$  and CS values were calculated using data from the spectroradiometric and Daysimeter data (see Table 4).  $CL_A$  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 0.1 (the threshold for circadian system activation) to 0.7 (response saturation), and is directly proportional to nocturnal melatonin suppression after 1-hour exposure (10% to 70%).<sup>17,18</sup> The following equations were used to determine  $CL_A$  and CS.

$$CL_A = \begin{cases} 1548 \left[ \int M c_\lambda E_\lambda d\lambda + \left( a_{b-y} \left( \int \frac{S_\lambda}{m p_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{m p_\lambda} E_\lambda d\lambda \right) - a_{rod} \left( 1 - e^{-\frac{\int V'_\lambda E_\lambda d\lambda}{RodSat}} \right) \right) \right] & \text{if } \int \frac{S_\lambda}{m p_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{m p_\lambda} E_\lambda d\lambda \geq 0 \\ 1548 \int M c_\lambda E_\lambda d\lambda & \text{if } \int \frac{S_\lambda}{m p_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{m p_\lambda} E_\lambda d\lambda < 0 \end{cases}$$

Where:

$CL_A$ : circadian light; the constant, 1548, sets the normalization of  $CL_A$  so that 2856 K blackbody radiation at 1000 lux has a  $CL_A$  value of 1000.

$E_\lambda$ : light source spectral irradiance distribution

$Mc_\lambda$ : melanopsin (corrected for crystalline lens transmittance) sensitivity

$S_\lambda$ : S-cone fundamental

$mp_\lambda$ : macular pigment transmittance

$V_\lambda$ : photopic luminous efficiency function

$V'_\lambda$ : scotopic luminous efficiency function

RodSat: half-saturation constant for bleaching rods =  $6.5 \text{ W/m}^2$

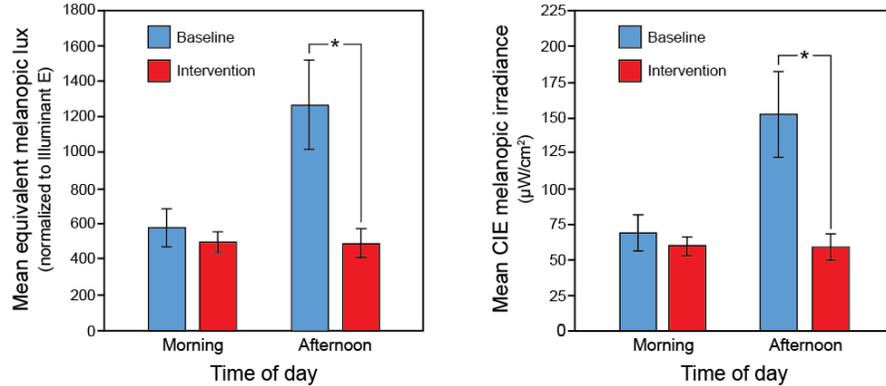
$k = 0.2616$

$a_{b-y} = 0.700$

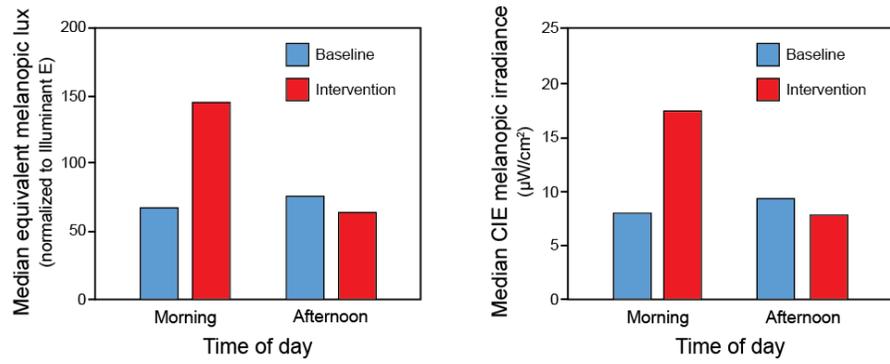
$a_{rod} = 3.300$

$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}}$$

Figure A shows the mean  $\pm$  SEM of the melanopic irradiance and equivalent melanopic lux (EML) values calculated using the Daysimeter data. It is interesting to note that, given the high variance in exposure, the average exposure during the intervention was lower than during baseline. In fact, the EML during baseline was significantly higher than during intervention in the afternoon. This is likely due to outliers, such as light exposure that may have occurred while a participant was outdoors. We then calculated the median values, which then showed that exposure was greater than baseline (Figure B).



**Figure A. Mean  $\pm$  SEM of the calculated EML (left) and melanopic irradiance. There was no significant difference between baseline and intervention values in the morning, while both the EML and the melanopic irradiance values were significantly greater at baseline than at intervention during the afternoon. Note that the red light intervention employed in the afternoon did not stimulate the melanopsin photoreceptor and had no impact on the measurements. These values are likely due to outdoor exposures.**



**Figure B. Median  $\pm$  SEM of the calculated EML (left) and melanopic irradiance. Unlike the mean values, the medians show greater values in the intervention than at baseline during the morning hours, when the blue light was applied. The fact that the median values are in the expected direction, but not the mean values, suggest that there is high variance in the exposures participants received during the study.**

## **APPENDIX 2: HOBO COMPLIANCE**

The HOBO devices (model HOBO UX90-005, Onset Computer Corporation, Bourne, MA) were installed to record when each participant's desk was occupied and when the desktop luminaire was energized. Three considerations have the potential to limit any firm conclusions that might be drawn from the HOBO data. First, if a desktop luminaire's location had been shifted, there is a possibility that the HOBO device might not have consistently detected an occupant's presence/absence. Second, because the desktop luminaire's design necessitated the magnetic attachment of the HOBO devices to a steel plate affixed to the front of the luminaire's base, the HOBO's sensors had the potential to be blocked by desktop materials such as keyboards, books, paperwork, etc. Finally, if extraneous light sources (e.g., daylight, task light, etc.) intermittently shined on the HOBO, its sensor could have erroneously detected that the luminaire was turned on.

In respect to these limitations, the HOBO data appear to indicate that a few of the sensors had been nudged from their initial, calibrated positions and thus registered that the luminaire was turned on during white light intervention only. Upon completion of the study, however, LRC researchers confirmed that all of the desktop luminaires were indeed still working as programmed. Furthermore, any issues relating to the HOBO devices' placement and subsequent performance appear to have been limited to their light-sensing function and not their occupancy-sensing function.

Beyond these limitations, some general conclusions can be drawn in respect to participant compliance:

1. The participants did not come to work on the Columbus Day federal holiday (October 9, 2017).
2. The desktop luminaires turned on automatically as programmed at 6:00 a.m. and turned off at 5:00 p.m., Monday through Friday, including the holiday (October 9, 2017). The luminaires did in fact stay off during weekends.
3. A few participants were apparently confused about when to turn on the desktop luminaire; 4 participants turned on the device for 1 minute, only once each, during the first 2 days of the baseline data collection period. One participant neglected to turn on the device on Day 1 of the intervention period and left it turned off until midday, but the participant was compliant thereafter. Three participants appear to have manually turned the desktop luminaire on and off during the intervention period, rather than relying on its automatic programming.
4. Several participants appear to have shifted the luminaire's location on their desks, which potentially explains why some participants might not have received the criterion CS value.
5. None of the compliance data were sufficiently compelling to result in excluding any participant's data from the project's analyses.