

# Circadian light and its impact on alertness in office workers: A field study

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## Abstract

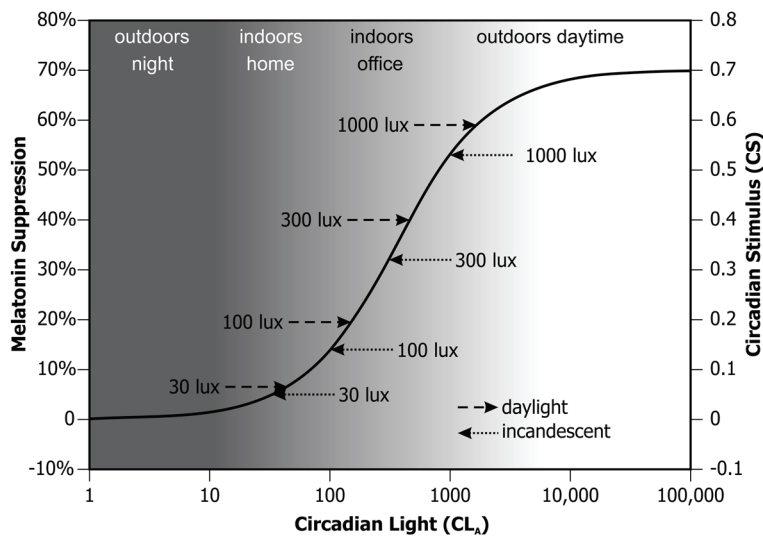
A field study was conducted at two federal office sites to demonstrate whether circadian-effective lighting (providing a circadian stimulus value of  $CS \geq 0.3$ ) could be installed in office buildings, and to determine whether this lighting intervention would increase alertness, vitality, and energy in office workers. Both desktop and overhead luminaires were used to provide circadian-effective lighting at participants' eyes in a two-day intervention. The Daysimeter device was used to measure participants' individual CS during the intervention and during a baseline, non-intervention day. Participants also completed questionnaires asking about sleep habits, stress, and subjective feelings of vitality and alertness. The Daysimeter data clearly show that participants were exposed to significantly higher amounts of circadian-effective light during the two-day intervention compared to the baseline day. Self-reported sleepiness scores were reduced, although the reduction was not statistically significant during the intervention compared to the baseline day. As hypothesized, participants reported feeling significantly more vital, more energetic, and more alert on the intervention days compared to the baseline day. Onsite photometric measurements demonstrated that both overhead and desktop luminaires using either cool-white or blue light can be used to deliver the desired CS to workspaces. Post hoc analyses showed that the use of these different lighting modes to deliver the intervention did not produce significantly different results.

## Introduction

The human circadian system is made up of biological rhythms that repeat approximately every 24 hours. The circadian system helps to keep people synchronized with the 24-hour day by regulating digestion, the release of certain hormones, body temperature, and when a person feels alert or sleepy. Light–dark patterns reaching the retinae are the major synchronizers of circadian rhythms to a person's local time on Earth. If left in darkness, the human circadian clock will free-run with a period that is slightly greater than 24 hours. Short-wavelength (blue) light delivered in the morning will promote entrainment by resetting the internal clock on a daily basis so that it runs with a period of 24 hours. At any time of day or night, light can also elicit an acute, alerting effect on humans, similar to a “cup of coffee.” Our research shows that saturated blue (peak close to 460 nm), saturated red (peak close to 630 nm), and white polychromatic light can elicit an alerting effect at any time of day and night (Sahin and Figueiro 2013; Sahin et al. 2014; Figueiro et al. 2016a).

Using published action spectrum data for acute melatonin suppression, Rea and colleagues proposed a mathematical model of human circadian phototransduction, which is how the retina converts light signals into electrical signals for the biological clock (Rea et al. 2005; 2012).

This model is also based on fundamental knowledge of retinal neurophysiology and neuroanatomy, including the operating characteristics of circadian phototransduction, from response threshold to saturation. Using this phototransduction model, the spectral irradiance at the cornea is first converted into circadian light (CL<sub>A</sub>), reflecting the spectral sensitivity of the circadian system, and then, second, transformed into circadian stimulus (CS), reflecting the absolute sensitivity of the circadian system. Thus, 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) (Fig. 1). It was hypothesized that a CS ≥ 0.3, a value nearly half of that outdoors *but* not commonly found in interior workplaces, would provide sufficient circadian stimulation to promote entrainment and alertness, and as a result, the CS metric has been successfully applied to quantify lighting interventions in numerous laboratory and field studies. In the laboratory, CS was used to predict melatonin suppression from self-luminous devices, and in the field, CS was used to predict entrainment in nuclear submariners, and sleep quality and mood in persons with Alzheimer’s disease living in senior facilities (Figueiro et al. 2014; 2016b; Wood et al. 2013; Young et al. 2015).



**Fig. 1. Modeled absolute sensitivity of the human circadian system.**

In a previous field study (Figueiro et al. 2017), we investigated the relationship between morning and daytime circadian-effective light and office workers’ sleep and mood. The results showed that office workers who received high circadian-effective light levels (CS ≥ 0.3) in the morning fell asleep faster at night (especially in winter), experienced better sleep quality, and had overall lower levels of depression compared to those who received low levels (CS ≤ 0.15) in the morning. High levels of circadian-effective light during the entire work day were also associated with reduced depression and increased sleep quality. Given these results, we conducted a follow-up field study, presented in this paper, to demonstrate: (1) whether circadian-effective lighting could be installed in office buildings, and (2) whether this lighting intervention would provide similar alertness and vitality in office workers. We hypothesized that a two-day exposure to a light level of CS ≥ 0.3 would increase alertness, vitality, and energy in office workers. Given the short duration of the intervention, this study was designed to

measure only the acute, alerting effects of light, and it is not known whether sleep may have improved as a result and, therefore, contributed to the observed results.

## **Methods**

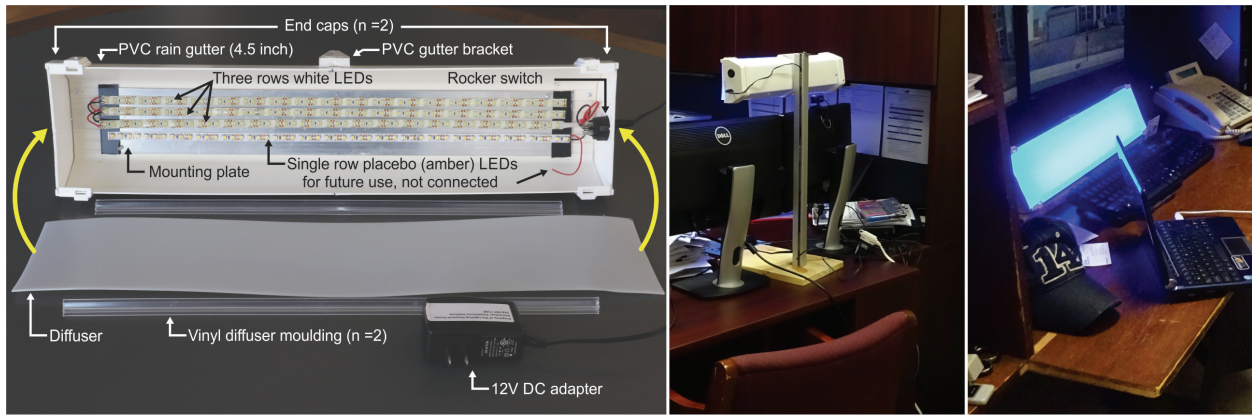
### ***Field study sites and participants***

Volunteers from the U.S. Department of Veterans Affairs (VA) Medical Center in White River Junction, Vermont, and the Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center in McLean, Virginia, participated in the study. At the VA office site, all participants worked in private offices and most had little or no access to daylight. Participants at the FHWA office site worked in both open-plan and private offices, and some desks had access to daylight while others were entirely windowless. Prior to the lighting intervention, baseline photometric analyses were conducted in the offices and desk spaces of participants to ensure that the lighting interventions used in the study would be of sufficient output to achieve the criterion CS value. Several participants at the FHWA site had access to daylight and were receiving a morning CS  $\geq 0.3$ . These participants took part in the study but did not receive any additional lighting intervention through supplemental electric lighting. Lighting intervention data were collected in summer (July to August 2016) and fall (October to November 2016). A total of 11 participants (8 females) from the VA site (mean age 48.3 yrs) and 25 participants (9 females) from the FHWA site (mean age 53.2 yrs) agreed to take part in the study in the summer. Of those, 8 participants (7 females) from the VA site (mean age 47 yrs) and 18 participants (7 females) from the FHWA site (mean age 53.2 yrs) agreed to repeat the study in the fall.

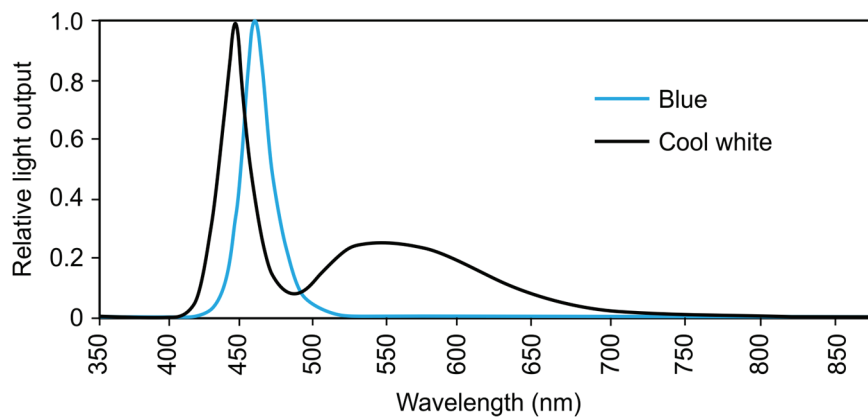
### ***Lighting interventions***

Because one goal of this study was to demonstrate that CS criteria can be achieved in several ways, multiple light source colors (i.e., cool white, blue, and color-tuning white) were used, and two types of luminaires (desktop and overhead) were developed or procured. The lighting interventions were developed based on the baseline, pre-intervention photometric analysis.

For desks and workspaces that would not easily permit the installation of additional overhead lighting, plug-in LED-based luminaires were developed for mounting on desktops near computer monitors, either on an elevated stand above the monitors or resting on office furniture below the monitors (Fig. 2). Seven narrowband, short-wavelength (470 nm) “blue” light and eight polychromatic “cool white” light desktop luminaires were built for the study, and their spectral power distributions are shown in Fig. 3. All of the luminaires were calibrated to deliver a CS of at least 0.3 at participants’ eye level, and calibration checks were performed onsite using a spectroradiometer. Because both desktop luminaires were designed and calibrated to deliver the same CS at the eye and no differences in outcomes were expected to exist between them, participants were permitted to choose either a cool-white or blue light desktop luminaire based on their preference. (Given that the cool-white luminaire had to deliver higher amounts of light to achieve the same CS as the blue light, some participants expressed a preference for the blue light.) Indeed, post hoc analyses showed no significant differences in participants’ responses that were based on the type of luminaire used during the study.



**Fig. 2.** Interior view of the white-light desktop luminaire built for this study (left; for the blue-light luminaire, two rows of blue LEDs replace the three rows of white LEDs shown here); desktop luminaire mounting options (center and right).



**Fig. 3.** Spectral power distributions of the cool-white light and blue light desktop luminaires built for the study.

The FHWA site provided an opportunity to install additional overhead lighting above eight desks. Desks equipped with additional overhead lighting did not receive desktop luminaires. The equipment employed in this intervention is a new type of lighting infrastructure called Power over Ethernet (PoE), which uses low-voltage data cabling to provide both power and control commands to LED luminaires via Ethernet. The overhead lighting and laptop/software system to control the luminaires were loaned by the manufacturer (Cree, Inc., Durham, NC).

The overhead luminaires were  $2 \times 2$  troffers that could be set for one of a range of color temperatures (3000K, 3500K, 4000K, 4500K, and 5000K) (Fig. 4). Light output could be dimmed indirectly by adjusting the specific occupancy sensor settings. Because participants did not have a manual switch to turn off their overhead lights when they left for the day, the integral occupancy sensors were programmed to turn off the lights after a time delay of 20 minutes.



Fig. 4. Examples of the  $2 \times 2$  troffers (indicated by the arrows) used as lighting intervention at the FHWA site.

### ***Data collection and protocol***

The Daysimeter, a calibrated light-measuring device, was used to collect personal light and activity data from the participants. The Daysimeter is calibrated in terms of orthodox photopic illuminance (lux) and of circadian illuminance ( $CL_A$ ), which is then converted to a CS value. Participants wore the Daysimeter during work hours so that the amount of CS they were exposed to during work could be determined.

Participants completed several questionnaires asking questions on sleep habits (Pittsburgh Sleep Quality Index [PSQI; Buysse et al. 1989] and Karolinska Sleepiness Scale [KSS; Åkerstedt & Gillberg 1990]), stress (Perceived Stress Scale [PSS-10; Cohen et al. 1983]), and subjective feelings about vitality and alertness (Subjective Vitality Scale [SVS; Ryan & Frederick 1997]). The Karolinska Sleepiness Scale (KSS) questionnaire 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 Subjective Vitality Scale (SVS) assesses participants' perceptions of feeling alive, vital, energetic or energized, alert, awake, and optimistic "at the present time." The participants' responses to seven individual statements were scored on a 7-point scale ranging from 1 (not at all true) to 7 (very true). These

questionnaires were selected because they have been used to probe participants' subjective sleepiness, vitality, and energy levels in previous studies.

The study was conducted over three days; baseline data collection was performed on Day 1 and intervention data collection was performed on Days 2 and 3. The protocol is presented in Table 1. The same Daysimeter, questionnaire, and logout routines were maintained between all experimental lighting conditions for each day of the study. At the end of Day 3, the participants placed their Daysimeters and completed questionnaires into a sealed envelope, which they submitted to the onsite point of contact for return to us. The protocol ran during the summer and was repeated during the fall.

**Table 1. Procedures employed in the experiment protocol for each day of the study.**

Procedure		Day 1	Day 2	Day 3
Wear Daysimeter at work (arrival to departure)		✓	✓	✓
Questionnaires	PSQI, PSS-10 (completed at arrival)	✓	–	–
	KSS, SVS (completed at arrival, 12:00 p.m., 3:00 p.m., and departure)	✓	✓	✓
Log time away from desk		✓	✓	✓
Experimental lighting condition	Desktop Luminaires	–	✓	✓
	Additional Overhead Luminaires <sup>a</sup>	–	✓	✓
	Daylight with Existing Luminaires (no additional luminaires) <sup>b</sup>	✓	✓	✓
Submit envelope containing questionnaires and Daysimeter to site contact		–	–	✓

Notes: (a) Procedure occurred at FHWA site only; (b) Procedure occurred at FHWA site only, and only among participants already receiving morning CS  $\geq 0.3$  as determined by baseline lighting assessments.

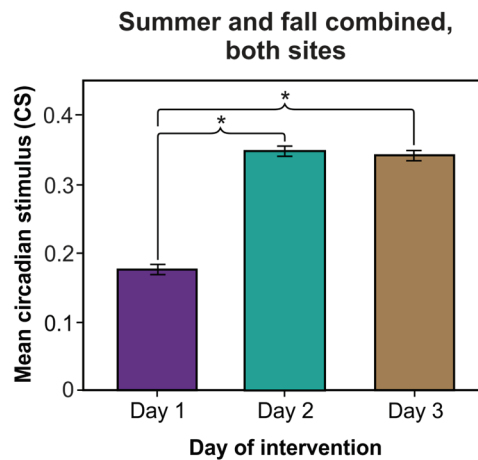
On Day 1, participants with the desktop luminaire kept it turned off in order to capture baseline lighting conditions. On Days 2 and 3, participants turned on their desktop luminaire upon arrival and left it on for the entire workday. Participants at the FHWA site who had the overhead luminaires installed were exposed to the lighting for the entire workday on Days 2 and 3 only. Because the additional overhead luminaires were centrally controlled without access to individual wall switches, participants exposed to this second condition conducted their Day 1 baseline assessment over an established period when the additional overhead lighting was turned off. Because Days 2 and 3 were not necessarily successive, the additional overhead lighting remained on over a period of several weeks. During the summer data collection, two participants experienced the overhead lighting prior to data collection for 12 days, one participant experienced it for 13 days, two participants experienced it for two days, and one participant experienced it for eight days. We did not observe any significant difference in responses between the participants who experienced the condition for two days and those who experienced it for 13 days. In the fall data collection, three participants experienced the lighting two days prior to data collection and two participants experienced it 12 days prior to data collection.

For the several participants at the FHWA site who had access to daylight and were already receiving a morning CS  $\geq 0.3$ , on Day 1 these participants were asked to close their window blinds to remove daylight in the space while the existing overhead lighting remained on. Upon arrival at work on Day 2, the participants were asked to open the blinds and leave them open until the end of the protocol. The existing overhead luminaires remained energized during Days 2 and 3.

## Results

### Daysimeter

Participants were exposed to significantly higher amounts of circadian-effective light on Days 2 and 3 when the lighting intervention was energized. In general, those working in the FHWA building received higher amounts of circadian-effective light than those working in the VA building. As expected, circadian-effective light was also greater during summer than fall months. Figure 5 illustrates the CS values obtained from the Daysimeters on Days 1, 2, and 3.



**Fig. 5.** Mean  $\pm$  standard error of the mean (SEM) circadian stimulus (CS) obtained from the Daysimeter during each of the 3-day protocol. Data presented are for seasons and sites combined. Day of intervention significantly affected CS values ( $F_{1, 2} = 223$ ;  $p < 0.0001$ ). Mean CS for Day 1 was significantly lower than for Day 2 ( $p < 0.0001$ ) and Day 3 ( $p < 0.0001$ ).

### Karolinska Sleepiness Scale (KSS) scores

Figure 6 illustrates the mean KSS scores throughout all times of day, for each day, and exhibits a U-shaped pattern. Lower KSS scores are associated with less sleepiness. KSS scores start relatively high upon arrival at work (mean  $\pm$  standard error of mean [SEM] =  $3.90 \pm 0.16$ ), fall at 12:00 p.m. (mean =  $3.59 \pm 0.11$ ), rise at 3:00 p.m. (mean =  $3.95 \pm 0.11$ ), and continue to rise at the end of the workday (mean =  $4.08 \pm 0.11$ ). This effect was also statistically significant ( $F_{3, 593} = 4.03$ ,  $p = 0.007$ ). Day of intervention came close to having a significant effect on KSS scores ( $F_{2, 597} = 2.81$ ,  $p = 0.061$ ). Across all times of day except for 12:00 p.m., KSS scores fell from Day 1 (mean =  $4.07 \pm 0.11$ ) through Day 2 (mean =  $3.84 \pm 0.11$ ) to Day 3 (mean =  $3.71 \pm 0.11$ ). Interestingly, the KSS scores for each time of day were widely divergent on Day 1. By Day 3, however, KSS scores for all times of day almost converged to the mean value, suggesting consistently greater alertness throughout the entire day as the protocol progressed.

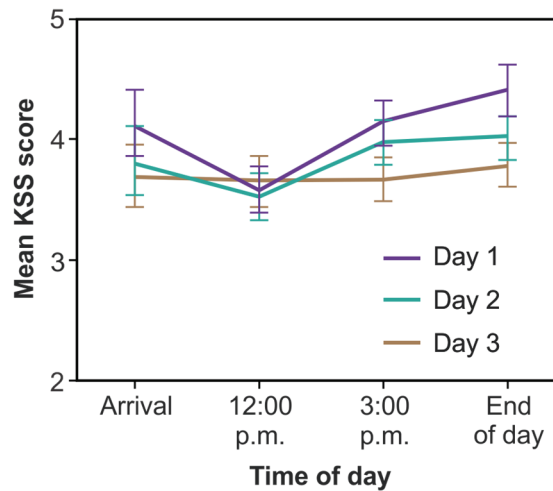


Fig. 6. Mean  $\pm$  standard error of the mean (SEM) KSS scores by time of day for all intervention days.

### Subjective Vitality Scale (SVS) scores

Figures 7 through 13 show the mean SVS score for each statement for each intervention day. Figures 8 through 11 and Figure 13 also show the mean SVS score by season (Statements 2, 3, 4, 5, and 7 only). Figure 12 shows the mean SVS score by building (Statement 6 only). For each statement, a higher score is associated with greater vitality, except for Statement 2 where a lower score is associated with greater vitality. In all cases, the day of intervention significantly affected the participants' responses to the SVS statements. Season also had a significant effect.

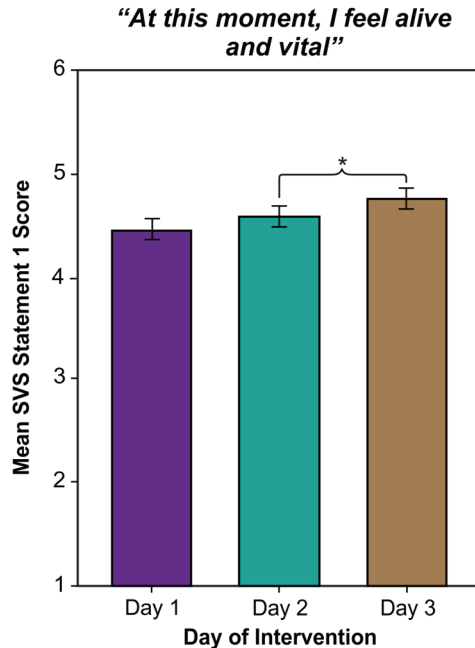


Fig. 7. Mean  $\pm$  standard error of the mean (SEM) SVS Statement 1 ("At this moment, I feel alive and vital") response scores for each intervention day. Day of intervention was the only factor that had a statistically significant effect ( $F_{2, 601} = 6.18, p = 0.002$ ) on participants' responses. The scores increased throughout all times of day, for each day, from Day 1 (mean  $\pm$  SEM =  $4.40 \pm 0.098$ ) through Day 2 (mean =  $4.53 \pm 0.090$ ) to Day 3 (mean =  $4.73 \pm 0.090$ ). Scores were significantly higher on Day 3 than on Day 2 ( $p < 0.01$ ).



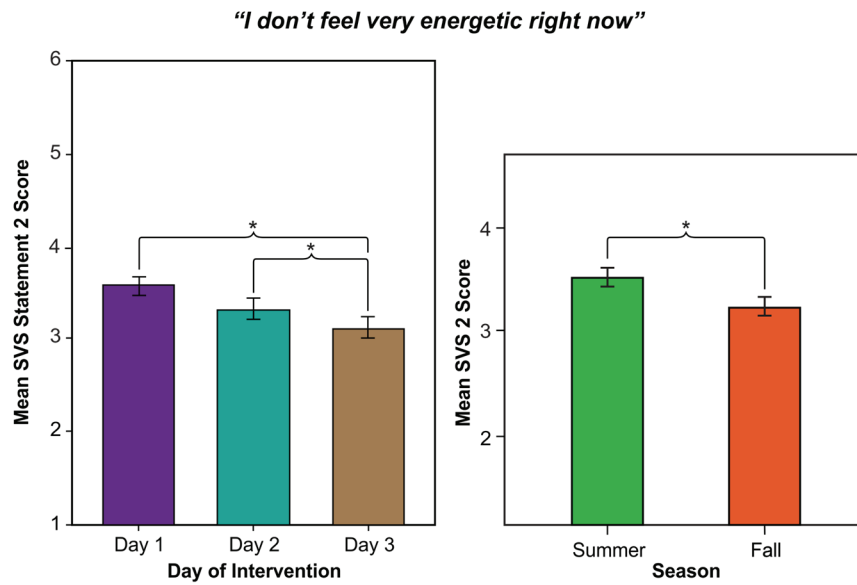


Fig. 8. Mean  $\pm$  standard error of the mean (SEM) SVS Statement 2 (“I don’t feel very energetic right now”) response scores for each intervention day (left) and by season (right). Day of intervention significantly affected ( $F_{2, 609} = 8.76, p < 0.0001$ ) participants’ responses. These responses were highest on Day 1 (mean  $\pm$  SEM =  $3.66 \pm 0.11$ ), falling through Day 2 (mean =  $3.40 \pm 0.10$ ) and Day 3 (mean =  $3.14 \pm 0.11$ ). Scores were significantly lower on Day 3 than on Day 2 ( $p < 0.05$ ) and Day 1 ( $p < 0.05$ ). Season also had a significant effect ( $F_{1, 627} = 8.79, p = 0.003$ ) on the responses to SVS Statement 2, with lower scores in fall (mean =  $3.24 \pm 0.09$ ) compared to summer (mean =  $3.52 \pm 0.09$ ).

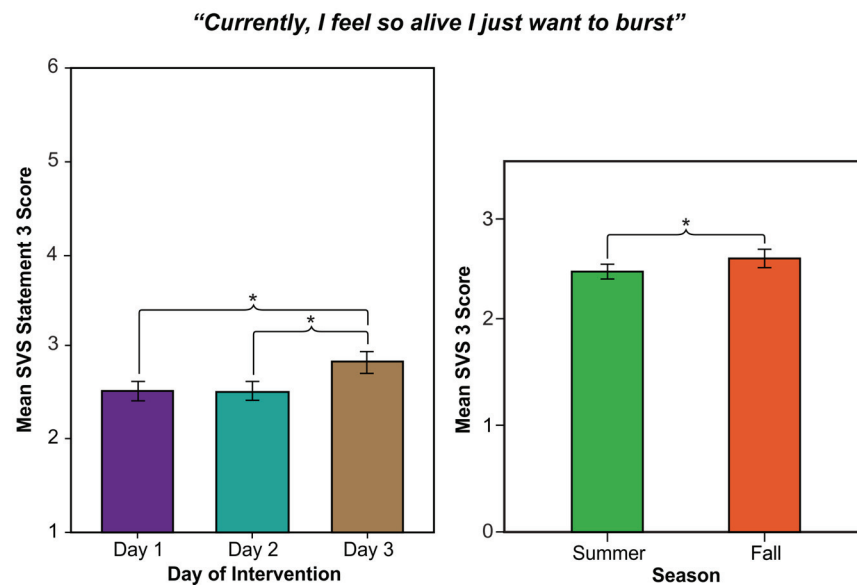


Fig. 9. Mean  $\pm$  standard error of the mean (SEM) SVS Statement 3 (“Currently, I feel so alive I just want to burst”) response scores for each intervention day (left) and by season (right). Day of intervention significantly affected ( $F_{2, 606} = 8.56, p < 0.0001$ ) participants’ responses. Across all times of day, their scores exhibited a slight downward trend from Day 1 (mean  $\pm$  SEM =  $2.46 \pm 0.11$ ) to Day 2 (mean =  $2.43 \pm 0.10$ ), and then increased to a greater degree on Day 3 (mean =  $2.73 \pm 0.11$ ). Scores were significantly higher on Day 3 than on Day 1 ( $p < 0.01$ ) and Day 2 ( $p < 0.0001$ ). Season also had a significant effect ( $F_{1, 611} = 8.07, p = 0.005$ ) on responses to Statement 3, with mean scores being slightly lower in summer (mean =  $2.48 \pm 0.08$ ) compared to fall (mean =  $2.61 \pm 0.09$ ).

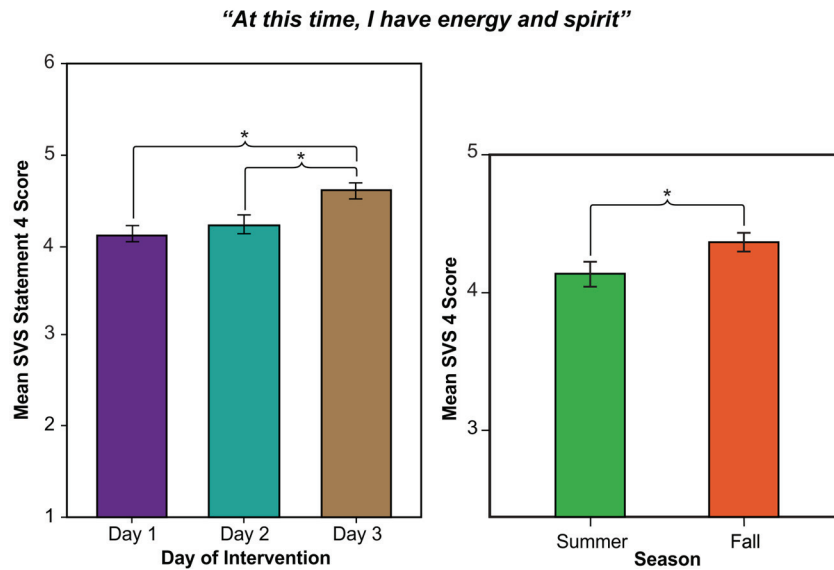


Fig. 10. Mean  $\pm$  standard error of the mean (SEM) SVS Statement 4 (“At this time, I have energy and spirit”) response scores for each intervention day (left) and by season (right). Day of intervention significantly affected ( $F_{2, 606} = 14.04, p < 0.0001$ ) participants’ responses. Across all times of day, scores were level or increased slightly from Day 1 (mean  $\pm$  SEM =  $4.03 \pm 0.10$ ) to Day 2 (mean =  $4.14 \pm 0.09$ ), and then increased to a greater degree on Day 3 (mean = to  $4.54 \pm 0.09$ ). Scores were significantly higher on Day 3 than on Day 1 ( $p < 0.0001$ ) and Day 2 ( $p < 0.0001$ ). Season also had a significant effect ( $F_{1, 620} = 4.56, p = 0.033$ ) on responses, with mean scores being lower in summer (mean =  $4.14 \pm 0.08$ ) compared to fall (mean =  $4.36 \pm 0.07$ ).

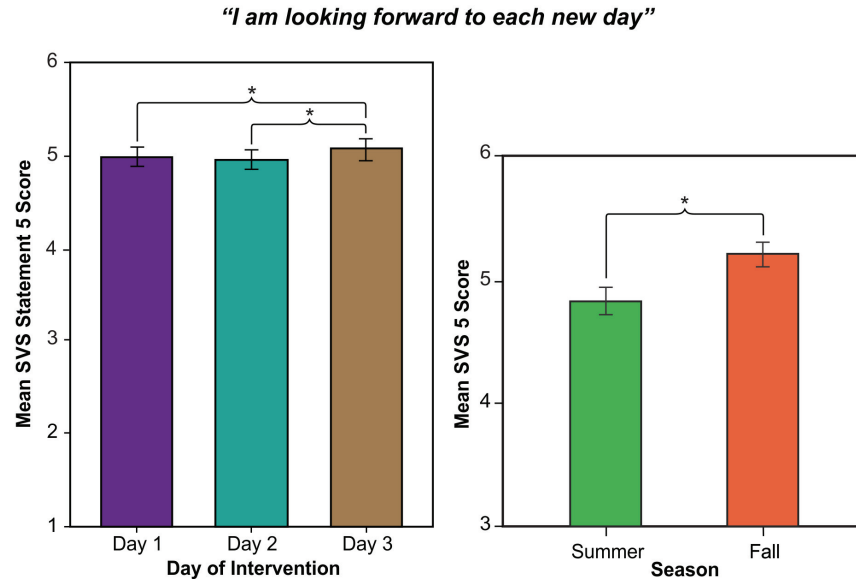


Fig. 11. Mean  $\pm$  standard error of the mean (SEM) SVS Statement 5 (“I am looking forward to each new day”) response scores for each intervention day (left) and by season (right). Day of intervention significantly affected ( $F_{2, 605} = 3.69, p = 0.026$ ) participants’ responses. Across all times of day, scores decreased slightly from Day 1 (mean  $\pm$  SEM =  $4.92 \pm 0.11$ ) to Day 2 (mean =  $4.89 \pm 0.11$ ), and then increased slightly on Day 3 (mean =  $4.99 \pm 0.11$ ). Scores were significantly higher on Day 3 than on Day 1 ( $p = 0.05$ ) and Day 2 ( $p < 0.05$ ). Season also had a significant effect ( $F_{1, 607} = 38.52, p < 0.0001$ ) on responses, with lower mean scores in summer (mean =  $4.85 \pm 0.08$ ) compared to fall (mean =  $5.21 \pm 0.08$ ).

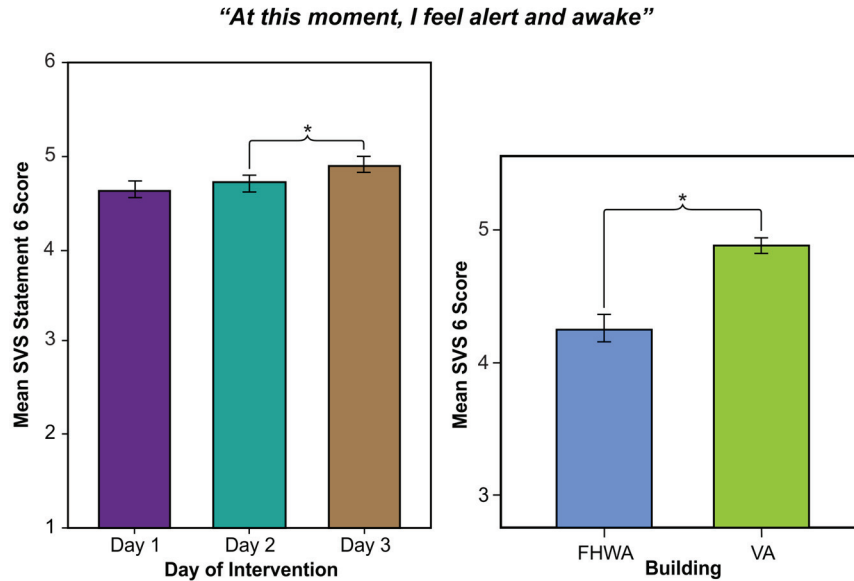


Fig. 12. Mean  $\pm$  standard error of the mean (SEM) SVS Statement 6 (“At this moment, I feel alert and awake”) response for each intervention day (left) and by building (right). Day of intervention significantly affected ( $F_{2, 608} = 3.67, p = 0.026$ ) participants’ responses. Mean scores increased steadily from Day 1 (mean  $\pm$  SEM =  $4.58 \pm 0.10$ ) through Day 2 (mean =  $4.64 \pm 0.10$ ) to Day 3 (mean =  $4.85 \pm 0.09$ ). Scores were significantly higher on Day 3 than on Day 2 ( $p < 0.01$ ). Statement 6 was the only SVS measure for which building had a significant effect ( $F_{1, 31} = 5.17, p = 0.03$ ) on scores. Mean scores recorded at the VA site (mean =  $4.90 \pm 0.06$ ) were higher than those at the FHWA site (mean =  $4.26 \pm 0.10$ ).

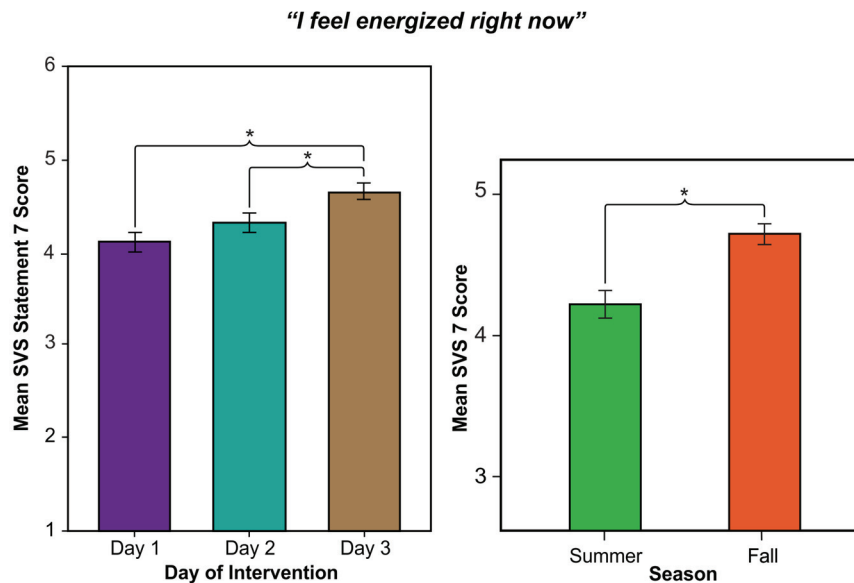


Fig. 13. Mean  $\pm$  standard error of the mean (SEM) SVS Statement 7 (“I feel energized right now”) response scores for each intervention day (left) and by season (right). Day of intervention significantly affected ( $F_{2, 609} = 9.02, p < 0.0001$ ) participants’ responses. Across all times of day, their scores increased from Day 1 (mean  $\pm$  SEM =  $4.26 \pm 0.11$ ) through Day 2 (mean =  $4.35 \pm 0.10$ ) to Day 3 (mean =  $4.70 \pm 0.10$ ). Scores were significantly higher on Day 3 than on Day 2 ( $p < 0.0001$ ) and Day 1 ( $p < 0.0001$ ). Season also had a significant effect ( $F_{1, 621} = 22.18, p < 0.0001$ ) on responses, with lower mean scores in summer (mean =  $4.24 \pm 0.08$ ) compared to fall (mean =  $4.70 \pm 0.10$ ).

## Discussion and Conclusions

The present study demonstrated that  $CS \geq 0.3$  during daytime hours is associated with an acute alerting effect on office workers. Although replication of these results in a larger group is warranted, these initial data are very promising. As we hypothesized, self-reported sleepiness (KSS) scores were reduced, although the reduction was not statistically significant ( $p = 0.06$ ) on Days 2 and 3 (i.e., during the intervention) compared to baseline Day 1. The KSS scores throughout the workday displayed a U-shaped pattern, with higher subjective sleepiness scores upon arrival and at the end of the day and lower scores (indicating less sleepiness) during midday. This pattern changed during the intervention. The KSS scores at each time of the day were divergent on Day 1, but by Day 3 the scores converged around their lower limit at all four time points, suggesting that subjective sleepiness remained lower throughout the entire workday. Season had no significant effect on sleepiness scores.

Also as hypothesized, the participants reported feeling significantly more vital, more energetic, and more alert on Days 2 and 3 (i.e., during the intervention) compared to baseline Day 1. Self-reports of vitality increased over the course of the day, indicating greater feelings of vitality at departure than upon arrival. Reported energy levels were greater in the middle of the day than they were upon arrival or at departure.

Onsite photometric measurements demonstrated that both overhead and desktop luminaires using either cool-white or blue light can be used to deliver the desired CS to workspaces. The use of different lighting modes to deliver the intervention did not produce significantly different results. New LED technologies that are now commercially available made it possible for us to deliver our target circadian-effective light in both private offices and cubicles, with and without access to daylight. Additionally, tuning the lighting intervention's spectrum to decrease the amount of light needed to deliver the desired CS level at the eye may be the most practical way to create more comfortable working environments.

An important consideration to keep in mind is that the lighting intervention was delivered for only two consecutive days and, moreover, that the study did not measure or control light exposures outside the work environment. Evening light exposures are just as important as morning light exposures when it comes to entrainment of the circadian system. Unexpectedly, we did not observe any seasonal effect on self-reports of sleepiness, and the seasonal effects that were observed on the vitality/energy scores were contrary to our expectation, as participants reported feeling more energetic and vital during fall rather than during summer.

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