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The impact of daytime light exposures on sleep and mood in office workers

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ABSTRACT

Background: By affecting the internal timing mechanisms of the brain, light regulates human physiology and behavior, perhaps most notably the sleep–wake cycle. Humans spend over 90% of their waking hours indoors, yet light in the built environment is not designed to affect circadian rhythms.
Objective: Using a device calibrated to measure light that is effective for the circadian system (circadian-effective light), collect personal light exposures in office workers and relate them to their sleep and mood.
Setting: The research was conducted in 5 buildings managed by the US General Services Administration.
Participants: This study recruited 109 participants (69 females), of whom 81 (54 females) participated in both winter and summer.
Measurements: Self-reported measures of mood and sleep, and objective measures of circadian-effective light and activity rhythms were collected for 7 consecutive days.
Results: Compared to office workers receiving low levels of circadian-effective light in the morning, receiving high levels in the morning is associated with reduced sleep onset latency (especially in winter), increased phasor magnitudes (a measure of circadian entrainment), and increased sleep quality. High levels of circadian-effective light during the entire day are also associated with increased phasor magnitudes, reduced depression, and increased sleep quality.
Conclusions: The present study is the first to measure personal light exposures in office workers using a calibrated device that measures circadian-effective light and relate those light measures to mood, stress, and sleep. The study's results underscore the importance of daytime light exposures for sleep health.

Introduction

Retinal light exposures affect human physiology and behavior by directly stimulating the brain's biological clock.[1] The daily pattern of light and dark falling on our retinas sets the timing of the biological clock, which most notably perhaps compels us to sleep at night and stay awake during the day in synchrony with Earth's 24-hour axial rotation.[2] The human circadian clock free-runs in constant darkness, generally with a period slightly greater than 24 hours. Sustained morning light is needed to advance, and therefore synchronize, the biological clock to local time on Earth.[3]

In contrast to foveal vision, on which most building lighting standards are based, the human circadian system requires high retinal exposures from short-wavelength light to be activated. Since electric lighting used in buildings is presently manufactured, designed, and specified only to meet visual requirements, the built environment may not provide a sufficient amount and the appropriate spectrum of light at the right time to stimulate the circadian system during the day. With the advent of self-luminous displays, there also may be too much light exposure during the night.[4–7] Irregular light–dark patterns or exposure to light at the wrong time may lead to circadian disruption and poor sleep quality, both of which have been associated with mood disorders, including depression, and with health risks such as diabetes, obesity, cardiovascular disease, and cancer.[8–14]

Consistent with the idea that reduced daytime light exposure might affect sleep quality and mood in office workers, Boubekri et al.[15] showed that office workers sitting close to windows, and presumably receiving higher amounts of light during the day than their colleagues in windowless offices, exhibited more activity overall and slept, on average, about 46 minutes longer at night. Office workers sitting close to windows also reported having better scores on the Pittsburgh Sleep Quality Index (PSQI) and the vitality scale of

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the Medical Outcomes Study 36-item short form health survey (SF-36). A limitation of the study was that light exposures were reported in terms of photopic illuminance using devices worn on participants' wrists. Figueiro et al.[16] showed that light level measurements recorded on the wrist are not well correlated with circadian-effective light at the eye. Moreover, photopic illuminance, defined in terms of the spectral sensitivity of foveal cones, peaking at 555 nanometers (nm), misrepresents circadian-effective light because the spectral sensitivity of the human circadian system peaks at approximately 460 nm. A more appropriate measure is circadian light (CL_A), which uses a spectral sensitivity function that best matches the response by the circadian system to light, as measured by acute melatonin suppression (discussed in Light exposure and activity measurements).

This rapidly evolving understanding of the circadian system led us to hypothesize that in buildings where daylight was a major design consideration, people would be exposed to lighting conditions that were sufficient to reliably entrain the circadian system to local time on Earth, especially in summer months. Specifically, we hypothesized that workers receiving morning circadian stimulus (CS) of ≤0.1, an exposure level needed for reliable measurements of nocturnal melatonin suppression in the laboratory,[17] would be less synchronized to the natural day–night cycle than those experiencing morning CS ≥0.3. As a corollary, we further hypothesized that those receiving morning CS ≥0.3 would exhibit better sleep quality and mood than those receiving morning CS ≤0.1.

To test these 2 hypotheses, participants were recruited from 5 different buildings managed by the General Services Administration (GSA), the largest landlord in the United States (US). GSA selected the buildings. Four of the buildings were selected because daylight considerations were incorporated in their original design (GSA Central Office, Washington, DC) or during extensive renovations undertaken between 2009 and 2013 (Edith Green–Wendell Wyatt Federal Building, Portland, OR; Federal Center South Building 1202, Seattle, WA; and Wayne N. Aspinall Federal Building and U.S. Courthouse, Grand Junction, CO). The fifth building (GSA Regional Office Building, Washington, DC), where daylight was not a major design consideration and many participants had little or no access to daylight, was selected as an experimental control. The selection was based on the notion that occupants in buildings with abundant daylight availability would be exposed to high levels of CS during work. Unfortunately, as we had usable data for only 5 participants in winter and 10 participants in summer from the non-daylit building, we do not have sufficient data to provide comparisons between participants from that building and the other 4 buildings.

Participants and methods

Participants

The study included 109 participants (69 females), of whom 81 (54 females) participated in both summer and winter (Table 1). One participant did not indicate their sex in the personal data. The total number of measurements obtained from these participants in both buildings for both seasons was 191 (124 from females); of those, 87 (58 from females) measurements were collected in summer and 104 (66 from females) were collected in winter. (Due to issues related to participant compliance and/or and the absence of useable data, the numbers of participants noted for the analyses reported in Results vary from the totals listed here.) All participants were federal employees from the 5 federal buildings selected for the study. All participants were employed as office workers; to a limited amount, some participants in the Seattle and Portland buildings conducted fieldwork. No exclusion criteria were applied in the selection of participants, as the study did not include a lighting intervention.

Generally, the participants in all 5 buildings received the Illuminating Engineering Society's recommended levels[18] (ie, approximately 30 footcandles [300 lux]) of horizontal illuminance at their desk spaces, although those from the Grand Junction and Portland facilities sometimes experienced lower levels during winter. Data collection in all 5 buildings was conducted between 2014 and 2016, and the analyses reported herein were conducted in the spring and summer of 2016.

Light exposure and activity measurements

Circadian light and circadian stimulus

Using published action spectrum data for acute melatonin suppression, Rea et al. proposed a mathematical model of human circadian phototransduction.[19,20] This model is also based on fundamental knowledge of retinal neurophysiology and neuroanatomy, including the operating characteristics of circadian phototransduction (converting light into electrical signals), from response threshold to saturation.[19,21] The intrinsically photosensitive retinal ganglion cells (ipRGCs) are the central elements in the phototransduction model, consistent with electrophysiological and genetic knockout studies.[22–27] The model also reflects neural input from the outer plexiform layer of the retina, consistent with studies showing that signals from rods and cones provide photic information to the ipRGCs.[21]

Using this phototransduction model, the spectral irradiance at the cornea is first converted into CL_A, reflecting the spectral sensitivity of the circadian system, and then, second, transformed into the 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).[28,29] Fig. 1 shows the modeled spectral sensitivity of the human circadian system at one light level (300 scotopic lux at the cornea) needed to determine CL_A at that light level, and Fig. 2 shows the absolute sensitivity of the human circadian system plotted as a function of CL_A. For reference, corresponding values for photopic illuminance, CL_A, and CS for common light sources (incandescent and daylight) are shown in Fig. 2.

Table 1
Total number of measurements by building and season

GSA building, location	Summer	Winter	Both	Total per building
GSA Central Office, Washington, DC	31 (16)	43 (22)	31 (16)	74 (38)
Edith Green–Wendell Wyatt Federal Building, Portland, OR	18 (13)	18 (13)	18 (13)	36 (26)
Federal Center South Building 1202, Seattle, WA	20 (15)	26 (17)	19 (14)	46 (32)
Wayne N. Aspinall Federal Building and U.S. Courthouse, Grand Junction, CO	7 (7)	11 (10)	7 (7)	18 (17)
GSA Regional Office Building, Washington, DC	11 (7)	6 (4)	6 (4)	17 (11)
Total number of measurements	87 (58)	104 (66)	81 (54)	191 (124)

Note: Number of measurements in females indicated in parentheses.

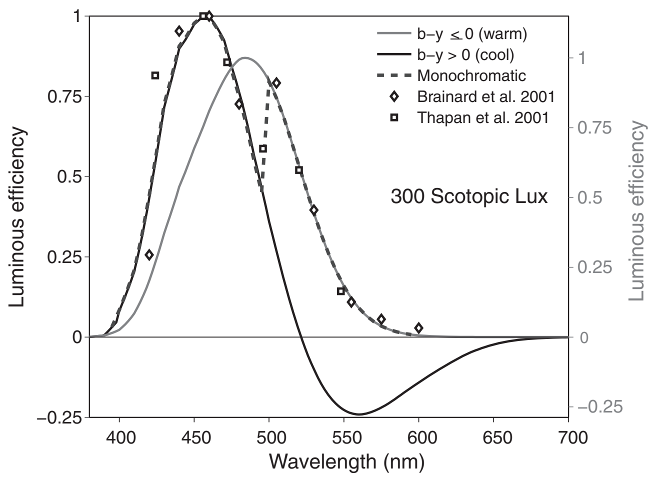

Fig. 1. The modeled spectral sensitivity of the human circadian system to narrowband light sources (dashed line) at a corneal illuminance of 300 scotopic lux; data points are the relative nocturnal melatonin suppression values published by Brainard et al.[30] (open diamonds) and by Thapan et al.[31] (open squares). Also shown are the modeled spectral sensitivity functions for 2 types of broad-band, polychromatic light sources, warm (solid gray line) and cool (solid black line). When a light source causes the blue versus yellow spectral opponent channel (b-y) to signal "yellow" (ie, for a warm light source), the spectral sensitivity is defined in terms of the photopigment melanopsin. When the b-y channel signals "blue" (ie, for a cool light source), the spectral sensitivity is defined in terms of melanopsin plus the short-wavelength sensitivity (S)-cone. Figure adapted from Rea and Figueiro.[32]

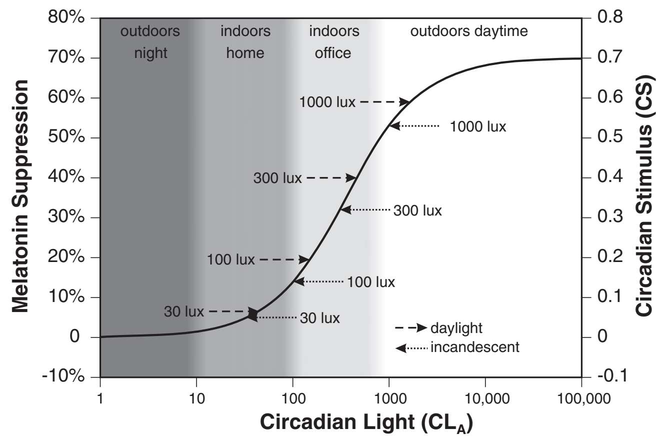

Fig. 2. The modeled absolute sensitivity of the human circadian system based upon nocturnal melatonin suppression. Circadian stimulus (CS) (right ordinate) is directly proportional to measured nocturnal melatonin suppression (left ordinate), and both measures are plotted as a function of CL_A, the corneal illuminance weighted by the spectral sensitivity functions in Fig. 1. Shown for reference are the ranges of indoor and outdoor light levels found in actual applications together with several daylight (dashed arrows) and incandescent (dotted arrows) corneal (photopic) illuminance levels. Note that for the same photopic illuminance, the daylight spectrum has a higher value of CS than the incandescent spectrum because daylight has relatively more short-wavelength energy to which the human circadian system is maximally sensitive. Figure adapted from Rea and Figueiro.[32]

The following equations show how CL_A and CS are determined.

$$CL_A = \begin{cases} 1548\left[\int Mc_\lambda E_\lambda + \left(a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda}E_\lambda d_\lambda - k\int \frac{V_\lambda}{mp_\lambda}E_\lambda d\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{Rodsat}}\right)\right)\right] & \text{if } \int \frac{S_\lambda}{mp_\lambda}E_\lambda D\lambda - k\int \frac{V_\lambda}{mp_\lambda}E_\lambda d\lambda > 0 \\ 1548\int Mc_\lambda E_\lambda D\lambda & \text{if } \int \frac{S_\lambda}{mp_\lambda}E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda}E_\lambda d\lambda \le 0 \end{cases}$$

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_λ	light source spectral irradiance distribution
Mc_λ	melanopsin (corrected for crystalline lens transmittance)
S_λ	S-cone fundamental
mp_λ	macular pigment transmittance
V_λ	photopic luminous efficiency function
V'_λ	scotopic luminous efficiency function
RodSat	half-saturation constant for bleaching rods = 6.5 W/m^2

$k = 0.2616$
$a_{b-y} = 0.7000$
$a_{rod} = 3.3000$

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

It should be noted that while CS was developed using data from studies that measured acute melatonin suppression, Zeitzer et al.[33] showed that acute melatonin suppression and phase shifting of melatonin rhythms followed similar threshold and saturation response characteristics. Moreover, the model has been successfully used to predict the effectiveness of various light sources and spectra for activating the circadian system in laboratory[17,34,35] and in field studies. For example, our field research with Alzheimer's disease patients, submariners, teenagers, and healthy older adults shows that exposure to a CS ≥0.3 at the eye, for at least 1 hour in the morning, improves sleep, mood, and behavior in these populations.[36–39]

The Daysimeter

The Daysimeter, a calibrated device that continuously measures light and motion, was used to collect personal light-exposure and activity data.[28] Light-sensing by the Daysimeter is performed via an integrated circuit sensor array (Hamamatsu model S11059-78HT) that includes 4 measurement channels: red (R), green (G), blue (B), and infrared (IR). The R, G, B, and IR photo-elements have peak spectral responses at 615 nm, 530 nm, 460 nm, and 855 nm, respectively. The Daysimeter is calibrated in terms of CL_A; CS is determined through post-processing of the recorded CL_A values. Recordings of activity–rest patterns were based upon the outputs from 3 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*) was determined using the formula:

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

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

Questionnaires

Participants completed 5 questionnaires concerning mood and sleep habits at the end of the study.

a. *Center for Epidemiologic Studies Depression Scale*
The Center for Epidemiologic Studies Depression Scale (CES-D) questionnaire is designed to measure depressive symptoms.[40] 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 of the time). Total scores range from 0 to 60, with scores ≥16 indicating greater depressive symptoms.

b. *Perceived Stress Scale*
The Perceived Stress Scale (PSS-10) questionnaire assesses participants' thoughts and feelings over the past month by posing 10 questions concerning how often they have thought or felt a specific way.[41] Answers are scored on a 5-point scale ranging from 0 (never) to 4 (almost always). Total scores ≥20 are considered to indicate high stress.

c. *Pittsburgh Sleep Quality Index*
The Pittsburgh Sleep Quality Index (PSQI) questionnaire is a subjective measure of sleep quality and patterns experienced for the majority of days and nights over the past month.[42] It differentiates poor from good sleep by measuring 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 of ≥5 indicates a poor sleeper.

d. *Positive and Negative Affect Schedule*
In the Positive and Negative Affect Schedule (PANAS) questionnaire,[43] subjective feelings about 10 positive affects (ie, interested, excited, strong, enthusiastic, proud, alert, inspired, determined, attentive, and active) and 10 negative affects (ie, distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, and afraid) are rated by participants on a scale ranging from 1 (very slightly or not at all) to 5 (extremely). Total scores range from 10 to 50, with higher scores representing higher levels of positive affect and lower scores representing lower levels of negative affect.

e. *Patient-Reported Outcomes Measurement Information System Sleep Disturbance–Short Form 8a*
The Patient-Reported Outcomes Measurement Information System (PROMIS) Sleep Disturbance–Short Form 8a questionnaire requests responses to 8 statements regarding sleep quality (e.g., my sleep was refreshing, I had difficulty falling asleep, my sleep was restless, etc.).[44] Answers are scored on a scale ranging from 1 to 5 (1 = very much, 2 = quite a bit, 3 = somewhat, 4 = a little bit, 5 = not at all). For this measure, raw scores are rescaled into a standardized T-score (mean $\pm$ standard deviation = 50 $\pm$ 10), with higher scores indicating greater sleep disturbance.

Protocol

Participants signed a consent form approved by the Institute Review Board at Rensselaer Polytechnic Institute. Once enrolled in the study, participants were asked to wear the Daysimeter as a pendant for 7 consecutive days during 2 data collection periods between: (1) December and February ("winter") and (2) late May and August ("summer"). Participants were instructed to maintain the device uncovered at all times. To permit monitoring of their sleep–wake activity patterns at night, the participants were asked to wear the Daysimeter on their wrist while in bed.

During the 7-day data collection period, participants were asked to keep a sleep log of bedtime and wake time, sleep latency, quality of sleep, and any naps taken. Participants in the Washington, DC, buildings had flexible schedules and were permitted to telecommute. These participants were asked to note: (a) the days in which they were in the office and (b) the desk space number they used during those days. All participants were free to choose their desk space for the day, and all desk spaces were equally available to each participant. In general, however, participants would stay in the same desk space, or at least in the same area in the office, for the entire week. The workers who were permitted to telecommute were asked to spend at least 3 days in the building during the data collection period.

The devices and questionnaires were mailed in sealed envelopes to the GSA staff volunteer serving as the on-site point person, who then distributed the envelopes to the participants. Upon completion of the 7-day data collection period, the staff volunteer collected the devices and questionnaires, again in sealed envelopes, and did not have access to any data at any time. The staff volunteer had no other role in the study, and no issues concerning this method of delivering/returning study materials from/to the researchers were reported.

Data analyses

a. *Circadian stimulus*
In terms of circadian-effective light exposures, we calculated the average CS during working hours in the building. These values were based upon self-reports from participants who were asked to record the days and times they were in the building. If this information was not available, we assumed their time in the building to be between 08:00 a.m. and 05:00 p.m. In addition, given that morning light is particularly relevant for circadian entrainment and that our main hypothesis was that better circadian entrainment would result in better sleep and mood, we calculated the CS exposure in the morning between 08:00 a.m. and 12:00 p.m. In order to test the hypothesis that a CS ≥0.3 was positively associated with better sleep quality and mood and less stress, the data set was divided into participants who were exposed to a CS ≥0.3 (high CS) and those who were exposed to a CS ≤0.15 (low CS). The low CS criterion was set at CS ≤0.15 to ensure a sample size comparable to that for the high CS criterion. (In a separate analysis, not reported here, we also tested the hypothesis using a low CS ≤0.1 and found similar results; however, only 6 subjects were included in the CS ≤0.1 group.) It is important to note that while measuring total light exposures over waking hours is needed to predict circadian entrainment,[45] the main goal of the analyses presented here was to understand how light at work affected sleep and mood. Therefore, we limited our analyses to morning and daytime light exposures.

b. *Light–dark and activity–rest synchrony (phasors)*
To quantify the degree of circadian entrainment exhibited by participants, the synchrony between their measured 24-hour light–dark pattern and their simultaneously measured activity–rest pattern was determined using phasor analysis. Phasor analysis operationalizes circadian entrainment in terms of a vector amplitude (magnitude) and phase (angle). In the phasor analysis conducted for the present study, light was measured in units of CS and activity in units of AI. Conceptually, the full set (e.g., 7 days) of light–dark and of activity–rest data are each joined end-to-end in a continuous loop. One loop is then rotated with respect to the other. Periodically (e.g., every 5 minutes), the correlation (r) between the light–dark data and the activity–rest data is computed, giving a correlation function for the entire data set. A fast Fourier transform (FFT) is applied to the resulting correlation function to compute a phase and amplitude vector for every frequency in the power spectrum.
The phase and amplitude vector, or phasor, for the 24-hour frequency is used to quantify circadian entrainment. The greater the phasor magnitude, the greater the synchrony between the light–dark and activity–rest patterns and, therefore, greater circadian entrainment is inferred. Dayshift nurses, for example, were found to have phasor magnitudes averaging about 0.5, whereas nurses on rotating shifts have phasor magnitudes averaging

about 0.1. This suggests, as would be expected, that dayshift nurses exhibit a high degree of circadian entrainment but rotating shift nurses exhibit a high degree of circadian disruption. Phasor angle, in hours, is a measure of the offset between the 24-hour activity–rest pattern and the 24-hour light–dark exposure pattern; a positive angle means that the activity pattern is delayed with respect to light exposure pattern and a negative angle means that activity pattern is advanced with respect to light exposure pattern. Typically, entrained individuals have a positive phasor angle of about 1 hour,[46] indicating low CS in the evening while people are still active.

For consistency with previously published phasor analyses,[37,46–50] the Daysimeter data collected during waking hours (when the device was worn as a pendant) were used in the analyses and light and motion data were set to zero during reported sleep times.

c. *Objective sleep analyses*

The Daysimeter sleep algorithm was developed as an analogue of the Actiwatch algorithm from the Actiware-Sleep Version 3.4 (Actiware-Sleep Version 3.4; Mini Mitter Co, Inc [now Philips Respironics, Murraysville, PA]). Modifications to the Actiwatch Algorithm were introduced to produce similar results using activity index (AI) provided by the Daysimeter instead of activity counts provided by the Actiwatch. The Daysimeter data obtained when the device was assumed to be worn on the wrist during the self-reported time-in-bed were used for the sleep analyses.

Every 90-second epoch during self-reported time-in-bed as well as 20 minutes before reported bedtime and 20 minutes after reported wake time was used as the sleep analysis period. Each of those epochs was scored as mobile or immobile based on whether the AI value for that epoch exceeded a "mobility threshold." The mobility threshold was defined as twice the "baseline activity," where baseline activity is the most frequent AI value greater than 0 and less than half of the maximum AI during the sleep analysis period. Usually, the average AI was non-zero when the Daysimeter was at rest because most of the accelerometers produce electronic noise. Epochs where AI was less than the Daysimeter's "mobility threshold" were scored as immobile, and epochs where AI was greater than or equal to the "mobility threshold" were scored as mobile.

In parallel, AI values during the sleep analysis period were transformed into "filtered activity" for every epoch (FA_i), where FA_i is a weighted moving average of AI for a given epoch (i) within the sleep analysis period. FA_i is computed from the AI value for that epoch (AI_i) together with the 2 AI epoch values occurring just before and the 2 AI epoch values occurring just after AI_i. Specifically,

$$FA_i = \frac{1}{25}AI_{i-2} + \frac{1}{5}AI_{i-1} + AI_i + \frac{1}{5}AI_{i+1} + \frac{1}{25}AI_{i+2}$$

where i designates the current epoch being evaluated.

Before the Daysimeter activity data could be scored as sleep or wake however, the AI_i values above the "mobility threshold" were used to set the "wake threshold" defined as 8/9 the average AI_i of epochs scored as mobile; FA_i values less than the "wake threshold" were scored as sleep.

Following the definitions from the Actiwatch algorithm, sleep onset latency, sleep time, wake time, and sleep efficiency were determined. Regardless of day of the week, only the nights after which participants reported being in the office were used in the sleep analyses.

d. *Subjective sleep analyses*

Scores obtained from self-reports of sleep quality, mood, and stress (see Questionnaires, above) were calculated and used in the statistical analyses.

e. *Statistical analyses*

All phasor results, objective sleep measurements collected via Daysimeter, and subjective sleep, stress, and mood measurements from questionnaires were submitted to mixed-model linear regressions using IBM SPSS Statistics 23.0 software (IBM Corp., Armonk, NY). In each regression, "participant" was entered as a random factor. Combinations of the following were entered as fixed factors: (1) season (summer or winter), (2) CS exposure in the morning on workdays (high versus low), (3) CS received during the entire workday (high versus low), and (4) CS throughout the workday (continuous variable). Interactions between CS measures and season were also submitted to mixed-model linear regressions. The results were considered significant if the associated p-value was ≤0.05. As described in each section, the results include measurements from only those participants who provided complete and/or usable data, and not necessarily all of the participants in the study.

Because of this study's longitudinal design, and because participants volunteered as part of their work duties, some did not complete all the data collection measures. Rather than dropping valuable data from the analyses, we chose to use mixed-model regression techniques that can produce valid results from data sets with missing points. The number of participants is relatively large for such a study, and the number of missing data points is relatively small, which should obviate some concerns that certain participants' data would have greater weight than others. Additionally, we contend the missing data are probably "missing at random." That is, those participants who did not complete data collection for a measure probably did not do so because of any factor related to the study design. For example, we do not believe that a participants' failure to complete a sleep questionnaire had anything to do with poor sleep quality.

Results

Table 2 lists the average and mean values and standard error of the mean (SEM) for the measures employed in the present study. Only those outcomes that were statistically significant are discussed below.

High versus low CS in the morning

Overall, 56 total participants were included in these analyses. Of those, 31 received high CS (≥0.3) between the time they arrived at work and 12:00 p.m., and 25 received low CS (≤0.15).

a. *Effects of high* versus *low CS in the morning and season on phasors*

Participants who had high CS during the morning hours showed a statistically significant effect on phasor magnitude ($F_{1,45} = 41.94$, $P < .0001$), suggesting greater circadian entrainment (Fig. 3). Phasor angle was significantly affected by season ($F_{1,6} = 37.72$, $P = .001$), irrespective of whether participants were exposed to high or low CS in the morning. Phasor angles in winter were higher than in summer. In general, a higher phasor angle in winter means that participants were active during the evening hours when CS values were low, while in summer, evening CS tended to be higher due to more daylight availability.

b. *Effects of high* versus *low morning CS and season on sleep measures and mood*

Receiving high CS exposure during morning hours had a statistically significant main effect on sleep onset latency ($F_{1,15} = 10.43$, $P = .005$). Participants who received low CS took longer to fall asleep than those receiving high CS during the morning (Fig. 4).

Table 2
Summary of mean values and standard error of the mean for light exposure and activity, objective sleep analyses, and subjective sleep analyses.

	Morning CS				Workday CS			
	High (≥0.3)		Low (≤0.15)		High (≥0.3)		Low (≤0.15)	
Measure	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Light exposure and activity (phasor)								
Circadian stimulus	0.35	0.01	0.12	0.004	0.35	0.01	0.11	0.004
Phasor magnitude	0.33	0.01	0.23	0.01	0.33	0.01	0.22	0.01
Phasor angle	1.04	0.17	1.40	0.20	0.96	0.18	1.51	0.16
Objective sleep analyses								
Sleep onset latency	17.99	2.59	44.91	8.25	20.70	3.03	25.06	5.93
Sleep time (min)	355.39	9.14	335.69	9.27	349.78	9.09	345.87	13.76
Wake time (min)	60.13	5.33	48.40	5.19	53.01	5.24	50.91	5.21
Sleep efficiency	76.87	1.55	74.06	1.85	77.52	1.62	76.37	2.00
Subjective mood and sleep analyses								
Total CES-D	4.75	0.76	8.19	1.15	5.71	0.84	7.03	0.98
PROMIS T-score	45.96	1.18	50.95	1.61	46.32	1.28	49.97	1.39
PANAS positive	33.38	1.01	29.86	1.89	32.46	1.21	32.03	1.40
PANAS negative	14.72	0.81	15.25	0.79	14.57	0.74	14.92	0.61
PSQI	4.72	0.39	7.15	0.54	5.54	0.46	6.64	0.46
PSS-10	12.31	1.35	12.29	1.70	11.83	1.46	13.44	1.15

Abbreviations: CES-D = Center for Epidemiologic Studies Depression Scale; CS = circadian stimulus; PANAS = Positive and Negative Affect Schedule; PROMIS = Patient-Reported Outcomes Measurement Information System, Sleep Disturbance–Short Form 8a; PSQI = Pittsburgh Sleep Quality Index; PSS-10 = Perceived Stress Scale; SEM = standard error of the mean.

High morning CS was also associated with significant results in several of the mood and sleep questionnaire measures (Fig. 4). Mean CES-D, for which lower scores indicate less depression, was significantly lower for participants with high morning CS ($F_{1,51} = 6.25$, $P = .016$). The mean PSQI, for which lower scores indicate better sleep quality, was also significantly lower for participants with high morning CS ($F_{1,44} = 9.48$, $P = .004$). Participants with high morning CS also reported significantly less sleep disturbance ($F_{1,39} = 11.67$, $P = .002$) as shown by their mean PROMIS T-score.

c. *Interaction between high* versus *low morning CS and season*
The benefit of having high morning CS was sometimes affected by season (Fig. 5). Seasonal interaction with CS was significant in the case of the PSQI measure ($F_{1,36} = 4.56$, $P = .040$). Participants with high morning CS reported higher PSQI scores in summer than in winter. The pattern was reversed for participants with low morning CS; they reported a lower mean PSQI score in summer than in winter.
In respect to PSS-10, for which lower scores indicate lower perceived stress, season also interacted with morning CS exposure ($F_{1,2} = 29.08$, $P = .041$), but for this measure there was no main effect of either season or CS. Participants with high morning CS had a higher mean PSS-10 score in summer than in winter. Participants with low morning CS exposure also had higher scores in summer than in winter.

Morning CS

The effect on measures of morning CS received between the time of arrival at work and 12:00 p.m. was analyzed for all participants, not just those who received the high or low CS. In general, morning CS had beneficial effects. The morning CS analyses included 173 measurements overall, 79 in summer and 94 in winter.

a. *Effects of morning CS and season on phasors*
The amount of CS received in the morning affected phasor magnitude (Fig. 6). As morning CS increased, so did phasor magnitude with significant effect ($F_{1,169} = 63.12$, $P < .0001$). Season had a significant effect on phasor angle ($F_{1,123} = 9.82$, $P = .002$), with higher phasor angles observed in winter than in summer.

b. *Effects of morning CS on sleep measures*
The PSQI scores also decreased with increasing morning CS ($F_{1,155} = 6.19$, $P = .014$ [Fig. 7]). The participants also reported less sleep disturbance, as their PROMIS T-scores decreased ($F_{1,165} = 4.76$, $P = .031$). Sleep onset latency declined as morning CS increased ($F_{1,162} = 13.49$, $P = .002$).
Season had a main effect on sleep onset latency ($F_{1,130} = 4.49$, $P = .036$), with shorter times reported in summer compared to winter (Fig. 8).

c. *Interaction between morning CS and season*
There was also a significant interaction between season and morning CS ($F_{1,123} = 4.19$, $P = .043$). Although sleep onset latency values decreased with increasing morning CS in both seasons, sleep onset latency decreased to a lesser degree in the summer.

High versus low workday CS

While receiving high CS in the morning is hypothetically the most beneficial for entrainment, receiving high levels of CS over an entire workday may still improve participants' sleep and mood. These analyses included 67 participants; 31 received high CS during the entire workday, and 36 received low CS during the entire workday.

a. *Effects of high* versus *low workday CS and season on phasors*
A pattern of significant effects on phasors emerged from our analysis of high versus low workday CS (Fig. 9). Participants who had high workday CS had greater phasor magnitudes than those who had low workday CS. This effect was statistically significant ($F_{1,39} = 35.38$, $P < .0001$). Phasor angle, on the other hand, was only significantly affected by season ($F_{1,36} = 6.08$, $P = .019$). Phasor angles during winter were greater than during summer (Fig. 9).

b. *Effects of high* versus *low workday CS and season on sleep measures and mood*
High workday CS had a significant main effect on participants' reported sleep quality and mood (Fig. 10). Participants with high workday CS had significantly lower PSQI scores than those with low workday CS ($F_{1,21} = 6.12$, $P = .022$). Participants with high workday CS reported significantly less sleep disturbance ($F_{1,33} = 10.44$, $P = .003$) as shown by the lower PROMIS T-scores.

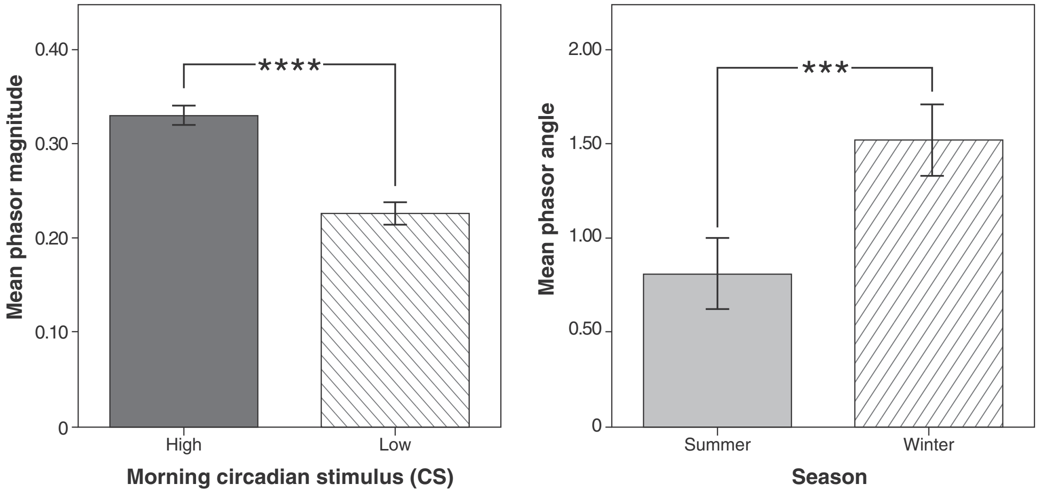

Fig. 3. The significant effects of high versus low morning CS on phasor magnitude and season on phasor angle. (The error bars represent standard error; **** designates a statistical significance at $P < .0001$ and *** designates a statistical significance at $P < .001$.)

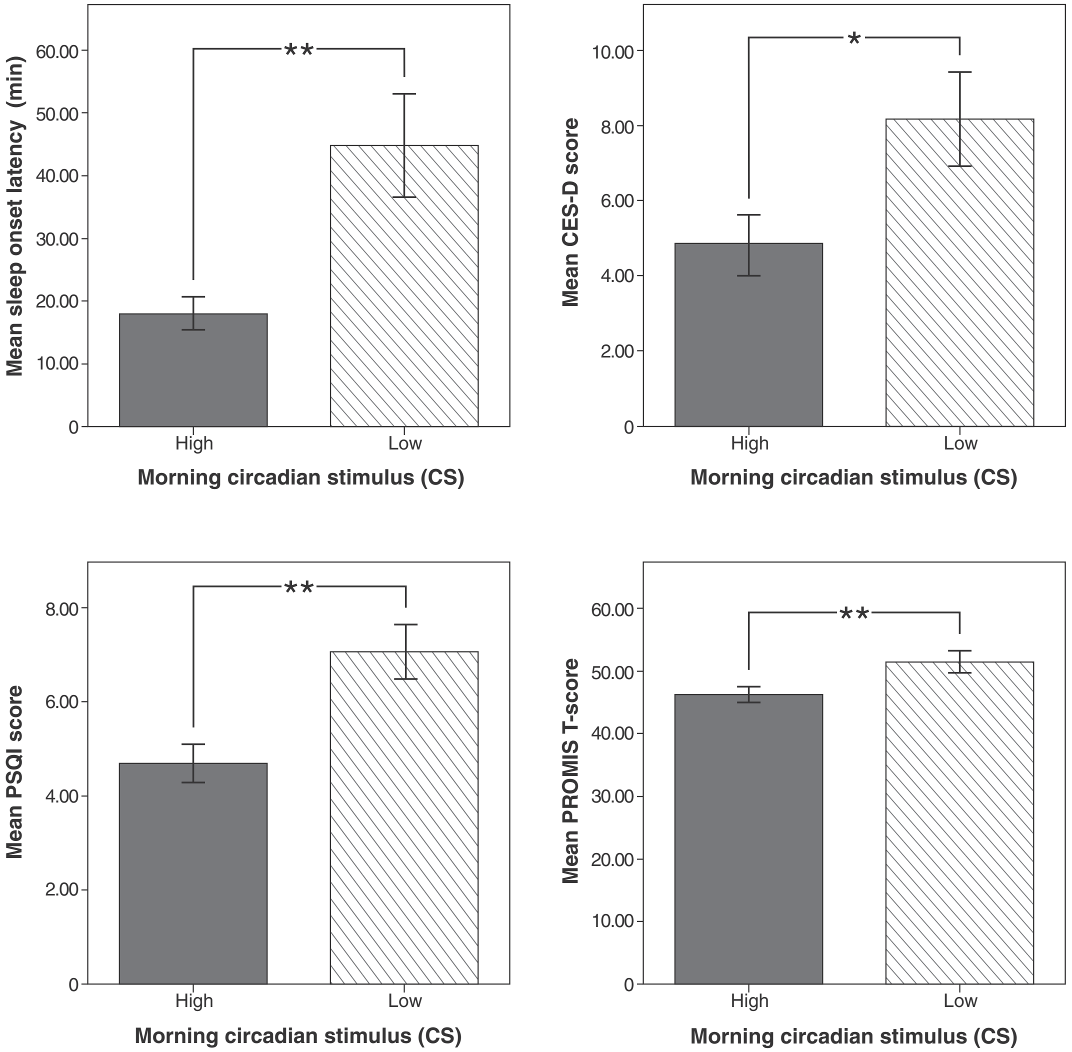

Fig. 4. The significant effects of high versus low morning CS on sleep onset latency, depression, and sleep quality measures. (The error bars represent standard error; ** designates a statistical significance at $P < .01$ and * designates a statistical significance at $P < .05$.)

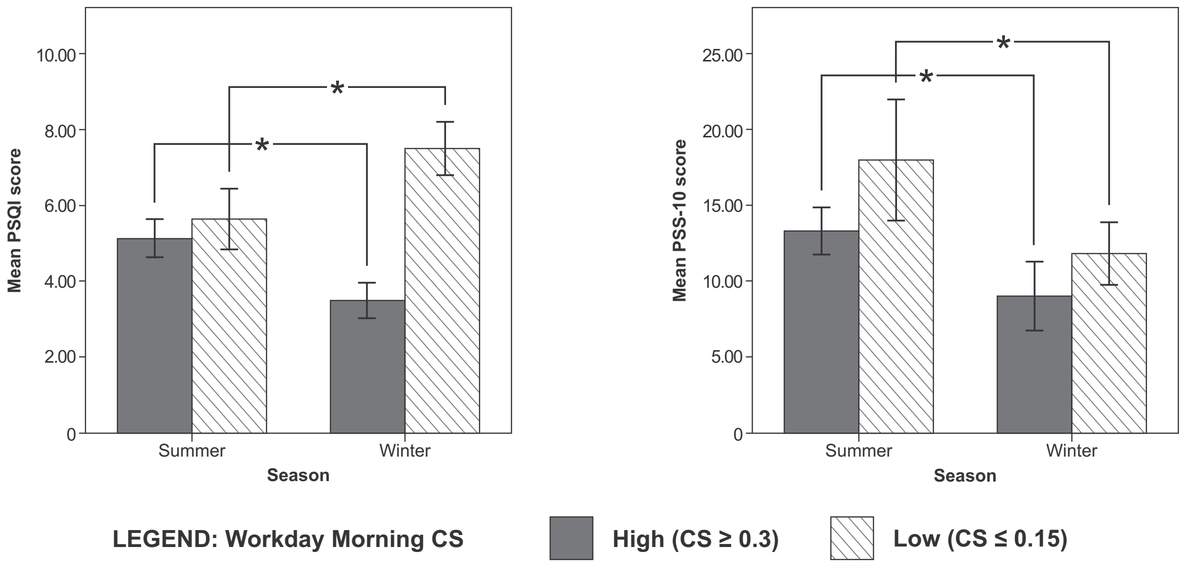

Fig. 5. The significant interactions between high versus low morning CS and season on mood and sleep quality measures. (The error bars represent standard error; * designates a statistical significance at $P < .05$.)

Finally, participants with high workday CS also reported significantly lower depression scores for the CES-D measure ($F_{1,44} = 4.68$, $P = .036$).

Season also had a significant main effect on mood outcomes (Fig. 11). Participants' mean PANAS Negative score was significantly higher in summer than in winter ($F_{1,18} = 5.56$, $P = .030$). The CES-D scores were significantly lower in winter ($F_{1,28} = 5.49$, $P = .026$) than in summer.

Discussion

The present study set out to determine whether exposure to high circadian-effective light in the workplace during the day, particularly in the morning, was associated with significant changes in circadian entrainment (phasor magnitude), objective sleep quality (sleep onset latency), subjective sleep quality (PSQI and PROMIS) and mood (CES-D and PANAS), as well as lower stress (PSS-10). These results are the first to demonstrate the utility of the CS metric for characterizing circadian-effective light in a field study.

Several findings are noteworthy. First, as hypothesized, higher CS exposure in the morning was associated with shorter sleep onset latency than lower CS exposure in the morning. This association was stronger in winter months, when the opportunity to receive light prior to arriving at work is reduced due to the later occurrence of dawn. These results are consistent with the findings of Vetter et al.,[51] who showed that office workers who were exposed to high correlated color temperature (CCT) light (8000 Kelvin [K]) for 5 consecutive weeks became entrained to light during working hours, whereas those exposed to a lower CCT (4000 K) at work exhibited a relatively advanced circadian phase that paralleled the seasonal progression of sunrise. (CCT is a specification used to describe a light source's dominant color tone, ranging from warm [yellows and reds] to cool [blue]. Lamps with a CCT rating <3200 K are usually considered warm sources, whereas those with a CCT >4000 K usually considered cool in appearance.) A high-CCT light source generally emits more short-wavelength radiation than a lower CCT light source, and therefore delivers higher CS values. Presumably, exposure to natural morning light before arriving at work served as the

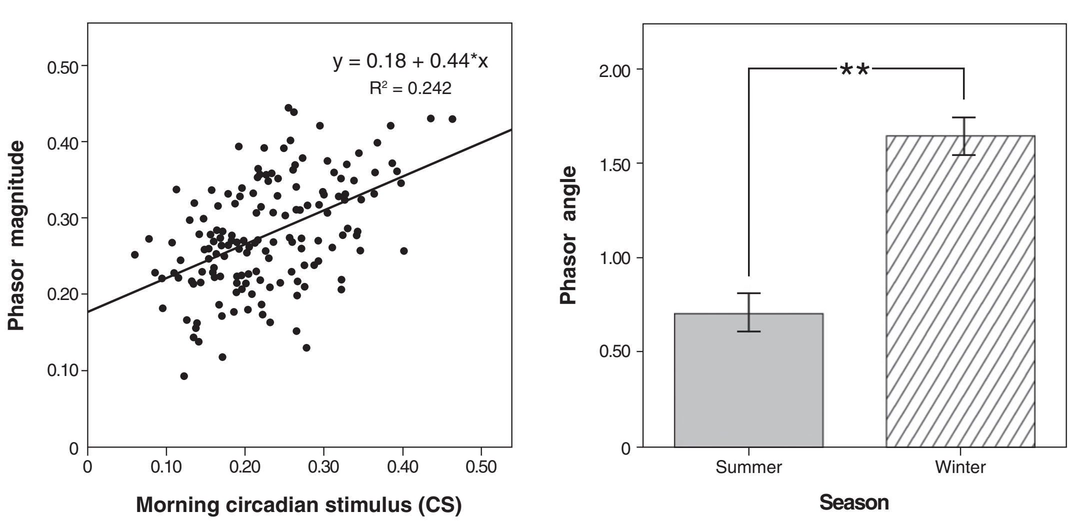

Fig. 6. The significant effects of morning CS on phasor magnitude and season on phasor angle. (The error bars represent standard error; ** designates a statistical significance at $P < .01$.)

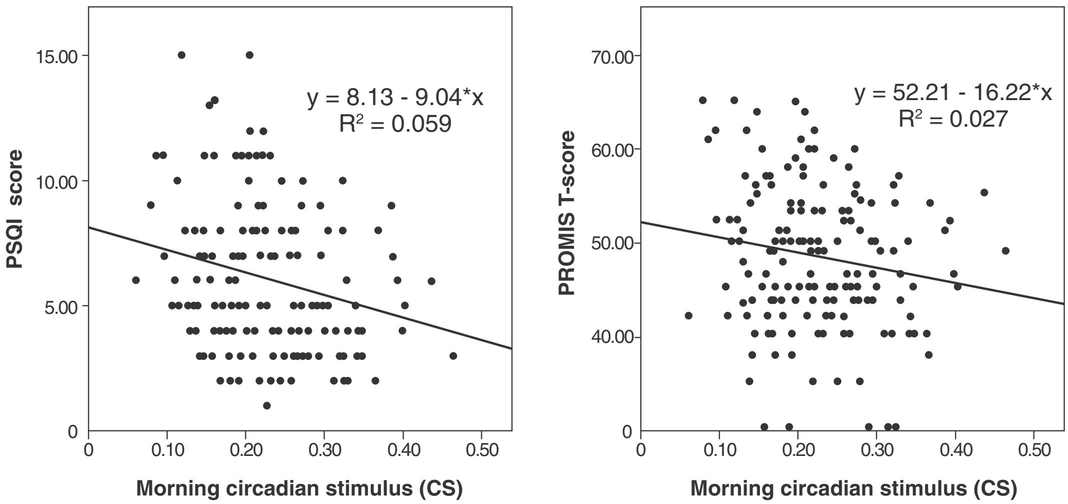

Fig. 7. The significant effects of morning CS on sleep measures.

primary entraining light for those in the low-CCT group, but office lighting served as the primary entraining light for those in the high-CCT group.

Second, consistent with our hypotheses, high CS exposure in the morning was associated with greater phasor magnitudes and better sleep quality (PSQI and PROMIS) than low CS exposure in the morning.

Although CS exposure in the morning and phasor magnitudes were unrelated to season, there were somewhat complicated interactions between levels of morning CS exposure and season in terms of both sleep quality (PSQI) and mood (PSS-10). With regard to PSQI scores, high CS in the morning was associated with better sleep quality than low CS exposure in the morning. Consistent with what might be expected, low morning CS was associated with decreased sleep quality in winter, but unexpectedly, high CS in the morning was associated with better sleep quality in winter than in summer. Although it is not possible to determine conclusively, this decrease in sleep quality might have been due to increased evening light/daylight in summer compared to winter. (In fact, our evening light exposure data [not reported here] and data reported by Crowley et al.[52] showed that workers do indeed receive more light in the evening hours during summer months than during winter.) Regarding PSS-10 scores, high CS in the morning was associated with lower self-reports of stress than low CS exposure in the morning during both summer and winter, but the difference between the 2 CS morning exposures was less pronounced during winter than during summer. It should be noted, however, that none of the other sleep quality and mood scores exhibited similar interactions. This might suggest that the statistically significant interactions associated with PSQI and PSS-10 might not manifest themselves again in a future study. These results may also be attributable to personal life events or lifestyles that had a stronger effect on self-reports than did individual light exposures.

Consistent with the findings associated with morning CS levels, high CS exposure during the entire workday was associated with greater phasor magnitudes than low CS exposure during the workday. High CS exposure during the entire workday was associated with lower depression scores (CES-D) and higher sleep quality (PSQI and PROMIS) scores than low CS exposure during the workday. Unlike the results of regression analyses relating CS during the morning to phasor magnitudes, CES-D scores, PSQI scores, and PROMIS scores, CS during the entire workday was not significantly related to these outcome measures. Nevertheless, it seems reasonable to infer that exposure to CS ≥0.3 during the day, particularly in the morning, was associated with better overall sleep quality and mood scores than exposure to CS ≤0.15. The CS metric has been successfully applied to quantify light intervention in many other laboratory and field studies. In the laboratory, CS was used to predict melatonin suppression from self-luminous displays,[53] and in the field CS was used

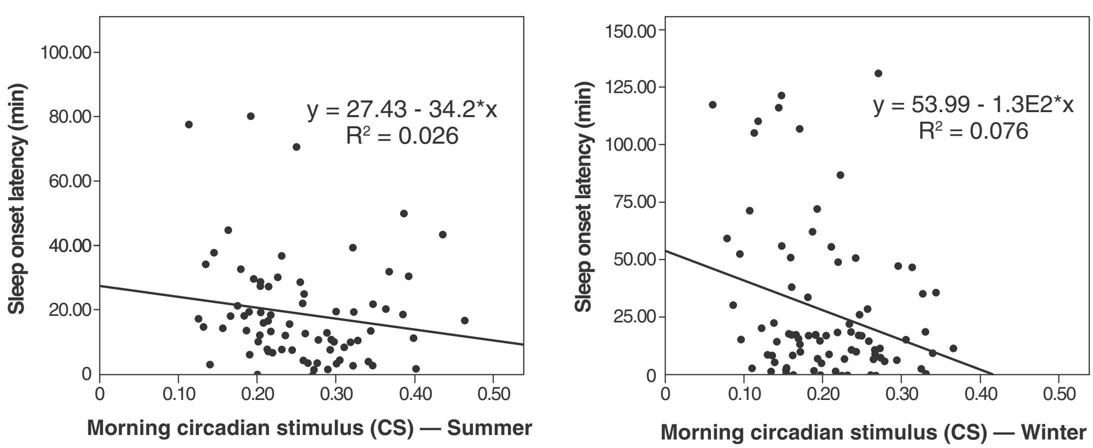

Fig. 8. The significant interaction between morning CS and season.

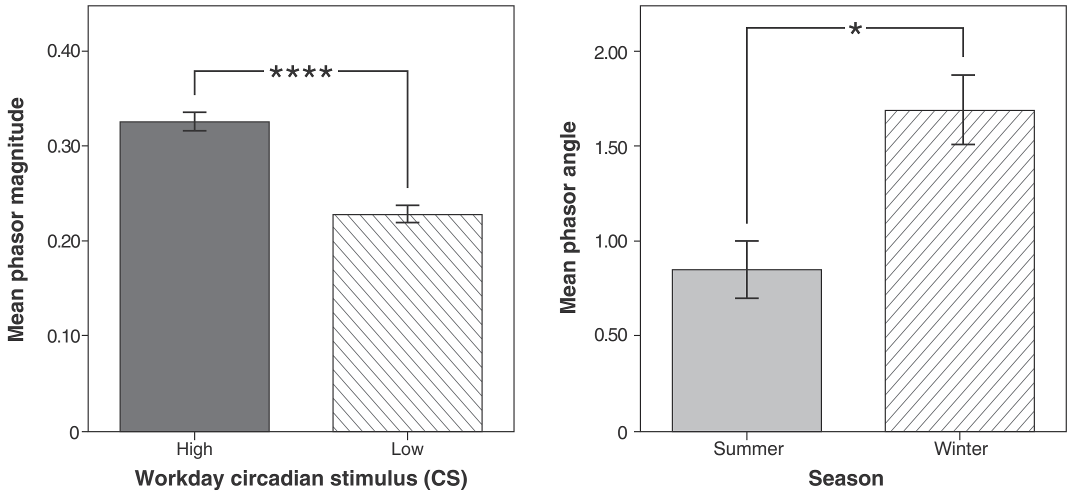

Fig. 9. The significant effects of high versus low workday CS on phasor magnitude and season on phasor angle. (The error bars represent standard error; **** designates a statistical significance at $P < .0001$ and * designates a statistical significance at $P < .05$.)

to predict entrainment in nuclear submariners,[37] and sleep quality and mood in persons with Alzheimer's disease and related dementia living in senior facilities.[49]

This inference is consistent with the results from Viola et al.,[54] who showed that exposure to a high-CCT light source reduced daytime sleepiness and increased self-reported sleep quality in office workers. Unlike Boubekri et al.,[15] who showed an increase in sleep duration for office workers sitting close to windows, and who should be receiving higher circadian-effective light, the present study did not show any significant association between CS exposure and actual sleep times. The participants in this study had an objectively measured mean sleep time of <6 hours, perhaps resulting from active social lives and personal obligations that limited longer sleep.

The mean sleep onset latency was close to 45 minutes for participants receiving low CS (CS ≤0.15) in the morning. These results suggest that greater phase delay in these participants was due to a lack of sufficient morning light, which is known to promote entrainment to the 24-hour solar day. Moreover, longer phasor magnitudes, which indicate greater behavioral circadian entrainment, are associated with those subjects receiving high CS (CS ≥0.3) values both during the morning and all day, and those reporting better mood and sleep. Importantly, promoting circadian entrainment in the built environment has been associated with better sleep as well as reduced stress and anxiety.[15] Sleep restriction, even after only a few days, has been linked to diabetes and obesity.[55,56] Chronic circadian disruption, such as that experienced by rotating shift workers over the course of many years, has also been associated with higher risk for cardiovascular disease and cancer.[57–60]

The present study is novel because it is the first to measure personal circadian light exposure in office workers using a device calibrated to measure circadian-effective light. It is also the first to directly relate circadian-effective light measures to mood, stress, and sleep outcomes. As with any field study, the present study has limitations. Perhaps most importantly, although the Daysimeter is a calibrated light meter, when worn as a pendant it does not measure light at the eye level and the CS exposures obtained from participants may be as much as 25% lower than those experienced at the eye level.[16] Furthermore, in this study it was assumed that workers spent their working hours inside their respective buildings, but it is unknown whether the CS measurements employed in our calculations were actually obtained inside or outside the office environment. Finally, while this study was not designed to measure social obligations and other personal issues, these may have affected the participants' self-reports of sleep, depression, and stress.

The results of this study are significant because they have the potential to inform building owners and designers about the importance of delivering appropriate light for the circadian system in the built environment during the daytime. One interesting finding was that the

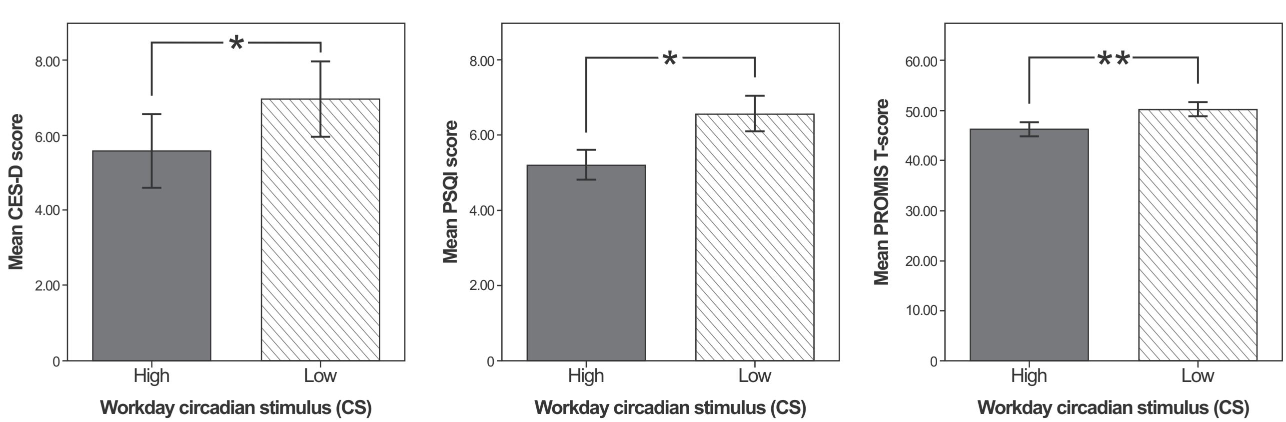

Fig. 10. The significant effects of high versus low workday CS on mood and sleep measures. (The error bars represent standard error; ** designates a statistical significance at $P < .01$ and * designates a statistical significance at $P < .05$.)

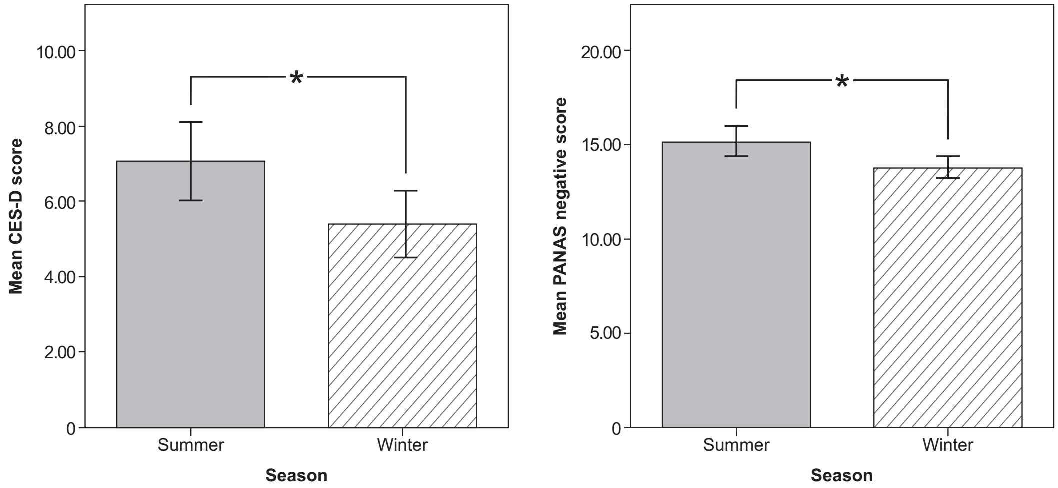

Fig. 11. The significant effects of season on mood measures. (The error bars represent standard error; * designates a statistical significance at $P < .05$.)

presence of daylight in a building does not necessarily ensure high CS exposure for workers. Most of the buildings studied here were designed to maximize daylight availability in the space, yet CS exposures did not always reach the desired criterion level of 0.3. Furniture placement, window shade positions, desk space locations and orientations, and visual and thermal comfort need to be taken into consideration when attempting to maximize exposure to CS in an office environment. Nevertheless, while much has been discussed about the detrimental effects of evening or night light on sleep and health, little attention has been paid to the importance of daytime light exposures, especially in winter months, on sleep health.

The present results can be considered as a first step toward promoting the adoption of new, more meaningful metrics for field research, providing the sleep research community with new ways to measure and quantify circadian-effective light.

Disclosure

The authors have no conflicts of interest to disclose.

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