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LIGHT, ENTRAINMENT, AND ALERTNESS: A CASE STUDY IN OFFICES

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Abstract

It is well established that light affects both the visual and non-visual systems. Laboratory studies have shown that, depending upon the time of exposure, short-wavelength light of sufficient amount and exposure duration will either entrain or disrupt the synchrony between our biological clock and our local position on Earth. Laboratory studies have also shown that light across the entire visible spectrum can enhance alertness, both day and night. Much less attention has been given to testing the effects of light on building occupants' non-visual responses. Consequently, lighting specifiers have been offered little guidance on the design and application of lighting for non-visual effects. This contribution helps to fill that gap through field-testing of light exposures from a novel luminaire designed to promote entrainment and alertness throughout the day in actual office environments. The data support the inference that light exposures, when properly applied, can promote circadian entrainment and increase alertness.

Keywords: Circadian Phase, Circadian Rhythms, Circadian Entrainment, Office Lighting, Light Level and Spectrum, Sleep, Alertness, Vitality/Energy

1 Introduction

Exposure to a robust 24-h light-dark cycle entrains people to their local position on Earth. Laboratory studies have clearly shown that short-wavelength (blue) light of sufficient amount and exposure duration can entrain or disrupt, depending upon the time of exposure, the timing of biological clock that controls our 24-h behavioural and physiological cycles. The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute developed 2 metrics, circadian light (CL_A) and circadian stimulus (CS) (Rea et al., 2005, Rea et al., 2012, Rea and Figueiro, 2018), to characterize light as a stimulus to the biological clock. CL_A and CS are based upon the effectiveness of a 1-h night-time light exposure for suppressing the hormone melatonin, a well-established marker of circadian phase (Benloucif et al., 2008). CL_A is irradiance weighted by the spectral sensitivity of the retinal phototransduction mechanisms stimulating the biological clock, and CS is a transformation of CL_A into a relative scale from response threshold (C < 0.1) to response saturation (CS = 0.7).

Light can also elicit an acute alerting response from humans (Cajochen et al., 2000, Cajochen et al., 2005) at any time of day (Okamoto et al., 2014). The lighting characteristics that promote alertness have been shown to be different from those promoting entrainment. In a series of laboratory studies (Sahin and Figueiro, 2013, Sahin et al., 2014), LRC researchers showed that exposure to long-wavelength (red) light can promote alertness during the mid-afternoon decline in performance known as the post-lunch dip. These findings are important for daytime applications in office environments because, unlike blue light, red light exposures in the afternoon can induce alertness without suppressing melatonin and affecting circadian phase.

Office lighting has traditionally focussed on supporting the human visual system without regard to light's non-visual effects, partly because current lighting standards are aimed at providing criterion levels of illuminance on the horizontal work plane. To provide these criterion horizontal illuminance levels, ceiling luminaires are most commonly specified. For light to be effective for entrainment and alertness, however, light must be delivered to the occupants' eyes, which are most commonly directed at the vertical plane in office environments. Thus, ceiling luminaires are not particularly effective for supporting the important non-visual effects of light. Since office workers spend most of their time indoors, entrainment and alertness can be compromised because they are exposed to too little light during the day from ceiling luminaires.

The overall goal of the present study was to evaluate whether a "non-visual layer of light" from a custom-built, desktop luminaire (Figure 1) would support office occupants' entrainment and alertness during the daytime. Subjective measures of sleep, alertness, and vitality/energy as well as objective measures of sleep and circadian phase were measured. Specifically, the research addressed 3 primary hypotheses:

1. Morning (06:00 to 12:00) blue light (CS ≥ 0,4) will promote entrainment and advance circadian phase. Sleep onset at night and sleep offset in the morning will be advanced relative to baseline following this light intervention. Activity acrophase will also be advanced.

2. Morning blue light (CS ≥ 0,4) will also elicit an acute alerting response from participants, reducing subjective sleepiness and increasing subjective vitality/energy.

3. Afternoon (13:30 to 17:00) red light (CS = 0) will elicit an acute alerting response, reducing subjective sleepiness and increasing subjective vitality/energy, especially at 15:00, close to the time of the post-lunch dip (Monk, 2005, Mitler et al., 1988). The 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 limiting a light-induced delay of circadian phase.
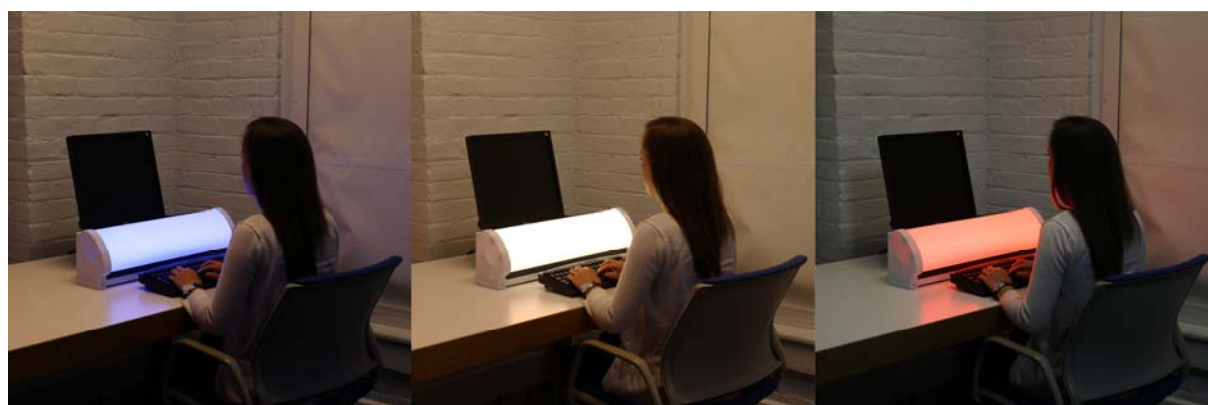

Figure 1 – The desktop luminaire used in the study, showing (left–right) the blue (06:00 to 12:00), white (12:00 to 13:30), and red (13:30 to 17:00) lighting intervention modes

2 Methodology

2.1 Participant Recruitment

Office worker participants were recruited from 3 United States Department of State (DOS) facilities: the Harry S. Truman Building (HST), Building SA-1 (SA-1), and Building SA-17 (SA-17), all located in Washington, DC, US (Table 1). Interested volunteers were enrolled in the study by the DOS following an information session explaining the study's aims and protocol. Twenty participants were enrolled, but one of them (#610 at SA-1) was excluded for a compliance-related concern (see 2.5 Data Analysis). There were no exclusion criteria for participation in the study.

Table 1 – Summary of demographic data for participants in this study, by site

Site	Mean (SD) Age (years)	Male (n)	Female (n)	Total (N)
Harry S. Truman Building	44,8 (14,5)	5	11	16
DOS Building SA-1	57,5 (2,1)	1	1	2
DOS Building SA-17	50,0 (7,0)	1	1	2
All Sites	46,7 (13,5)	7	13	20

After enrolment, the desktop luminaires were installed on participants' desks and the researchers distributed packages containing a Daysimeter, an actigraph, and 5 sets of questionnaires. The protocol was explained once again, consent forms were obtained, and answers were provided for any participants' questions. One employee from each location served as the on-site point of contact, and that individual 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, beginning on 2017-09-25 and ending on 2017-11-03 (see 2.4 Protocol). 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 (see Table 1).

2.2 Measurement Procedures

2.2.1 Devices

The Daysimeter, a light-measuring device developed by the LRC (Bierman et al., 2005), was used to collect personal light exposure data from the participants. The Daysimeter is calibrated in terms of orthodox photopic illuminance (lx), circadian light (CL_A), and circadian stimulus (CS) (see 1 Introduction). To estimate their CS exposures while awake, participants wore the Daysimeter suspended from a lanyard from the time they woke up in the morning until they went to bed at night. Participants were asked to remove the Daysimeter when going to bed. It is not known whether they performed activities such as using self-luminous personal electronic devices (PEDs) before falling asleep. The researchers assumed that the participants would not substantially change their behaviour before bed from week to week, so any additional circadian stimulus from PEDs was hypothesized to be constant during the study period.

Participant's rest–activity patterns were measured via wrist actigraphy (Philips Actiwatch Spectrum Plus, Philips Respironics, Murrysville, PA, US), which were recorded 24-h/day during weeks 1 and 3 of the study, excluding weekends (see 2.4 Protocol). The Actiwatch is equipped with a highly sensitive accelerometer that measures and records users' activity and the time(s) at which the device was worn. 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 amount of time between going to bed and falling sleep (in minutes); (4) sleep efficiency, or the proportion of time spent in bed while actually asleep (percentage); (5) sleep time, or the amount of time between sleep start time and sleep end time that is scored as sleep by the Actiware software (in minutes); and (6) wake time, or the amount of time between sleep start time and sleep end time that is scored as wake by the Actiware software (in minutes).

The actigraph data were also used to calculate interdaily stability (IS) and intradaily variability (IV) (Van Someren et al., 1997). The IS ratio quantifies the extent to which all recorded 24-h 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, which is the phase angle of a 24-h cosine fit to the actigraph activity data using the method of least squares (Refinetti et al., 2007). This measure reports results as the time of day at which activity was at its maximum. Activity acrophase is a measure of circadian timing; an earlier activity 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 activity acrophase to occur earlier in the day after the intervention.

2.2.2 Questionnaires

Participants completed a series of questionnaires. Participants' sleep habits were assessed using the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) and Karolinska Sleepiness Scale (KSS) (Åkerstedt and Gillberg, 1990). Subjective feelings of stress were assessed using the Perceived Stress Scale (PSS-10) (Cohen and Williamson, 1988), depression was assessed using the Center for Epidemiologic Studies Depression Scale (CES-D), and vitality and alertness were assessed using the Subjective Vitality Scale (SVS) (Ryan

and Frederick, 1997). The schedule for participants' completion of the questionnaires is provided in 2.4 Protocol. These questionnaires were selected because they have been used to probe participants' subjective sleepiness, vitality, and energy levels in previous studies.

2.3 Lighting Interventions

The LRC developed and built 20 plug-in LED luminaires for mounting on desktops near participants' computer monitors (see Figure 1). The luminaires were designed to deliver 3 lighting interventions: (1) saturated blue light in the morning (06:00 to 12:00), (2) white light at midday (12:00 to 13:30), and (3) saturated red light in the afternoon (13:30 to 17:00). Gradual transitions between each lighting intervention were accomplished in 1 min. The desktop luminaires automatically turned off at 17:00 and remained off until 06:00 the next day. The specifications for the 3 lighting interventions are shown in Table 2, and their spectral power distributions are shown in Figure 2.

Table 2 – Specifications of the desktop luminaires and the times each lighting intervention was applied. Note that for the white light intervention, a higher light level was required to achieve the criterion CS value ≥ 0,3 compared to the saturated blue light intervention

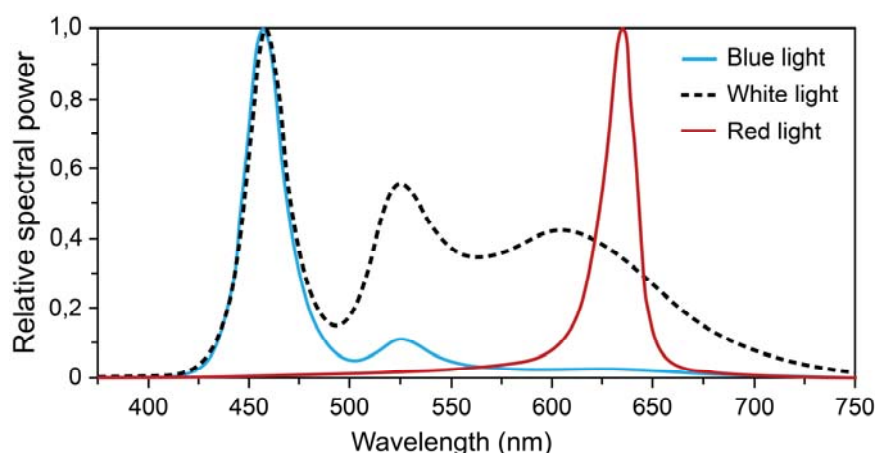| Time of Day	Lighting Intervention	λ_{max} (nm)	E_V (lx)	CS
06:00 to 12:00	blue	455	50	0,40
12:00 to 13:30	white (6500 K)	n/a	200	0,30
13:30 to 17:00	red	634	50	0

Figure 2 – Spectral power distribution of the desktop luminaire's 3 lighting interventions

The custom-built desktop luminaires used to deliver the lighting interventions each housed 2 high-output linear accent, RGB colour-tuneable LED luminaires (model G2, Ketra, Austin, TX, US) that were aligned end to end and covered by a domed, translucent acrylic light diffuser (Utilitech Pro Wrap shop light, Lowe's, Mooresville, NC, US). The luminaires were pre-programmed for the desired output modes (i.e., spectrum and light level), driven by a dedicated satellite link controller (model N3, Ketra), and equipped with a touchpad interface (model X1, Ketra). Each desktop luminaire measured approximately 60 cm long × 20 cm high × 20 cm deep.

The blue lighting intervention was selected for the morning to promote alertness and circadian entrainment by providing a high stimulus (CS ≥ 0,4) at the occupants' eyes. This intervention was expected to support circadian entrainment by providing a daily, robust light stimulus that would counteract the natural phase delay of the biological clock. It was also expected to either advance occupants' sleep start times or, for those already entrained, reinforce their existing sleep start times. The white (6500 K) lighting intervention was selected for midday to provide a smooth transition from the blue to the red light, while still delivering an entraining stimulus (CS ≥ 0,3) to the occupants' eyes. The red lighting intervention was selected for the afternoon to provide an alerting stimulus while minimizing circadian-effective light during the latter part of the day, thereby preventing the delay of circadian phase.

On 2017-09-20 and 2017-09-21, 16 desktop luminaires were installed at the HST site, 2 luminaires were installed at the SR-1 site, and 2 luminaires were installed at the SR-17 site. On-site photometric measurements were obtained for each installed device. Each desktop luminaire was positioned at a 30º tilt to direct most of the light toward the participant's eyes. The linear luminaire remained in that position for the duration of the study.

On-site photometric measurements were obtained using an optical spectrometer (Model USB650 Red Tide Spectrometer, Ocean Optics, Winter Park, FL, US) or illuminance meter (Model BTS256-E, Gigahertz-Optik, Türkenfeld, DE). The spectroradiometer was used in conjunction with software written by the LRC to calculate CS values. Measurements were recorded at each occupant's eye level while seated at their desk, first with the desktop luminaire turned off, followed by a measurement for each of the desktop luminaire's 3 lighting intervention modes (totalling 4 measurements per device).

2.4 Protocol

Each study session was conducted over 3 successive 1-week periods with 2 cohorts of participants experiencing the same series of lighting interventions. The first session was conducted between 2017-09-25 and 2017-10-13 and the second session was conducted between 2017-10-16 and 2017-11-03. The same protocol was followed by both cohorts (Figure 3). Baseline photometric data were collected during week 1, prior to administration of the lighting interventions during weeks 2 and 3. Upon arrival at the office on the first day of week 1, each participant wore a Daysimeter around their neck as a pendant from the time of their arrival at work until bedtime, and the actigraphs were worn on the wrist 24 h/day (even while bathing) during each day of the protocol in weeks 1 and 3. The Daysimeters and actigraphs were not worn on weekends, remaining in sealed packages at the participants' workstations from departure on Friday until arrival on the following Monday. Participants were also asked to fill out the 5 questionnaires (i.e., PSQI, KSS, CES-D, PSS-10, and SVS) on the first day of week 1. The 2 questionnaires inquiring about participants' subjective feelings of sleepiness, vitality, and energy (i.e., KSS and SVS) were filled out 3 more times that day, and 4 times per day on every day of the baseline week.

Upon arrival at work on the first day of week 2, participants were instructed to energize the desktop luminaires, which cycled throughout the workday according to the lighting 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 reasons for this were 2-fold. First, as we were interested in the longer-term effect of the intervention, the first lighting intervention week served as an acclimation week. Second, we wanted to minimize any undue burden on the participants and thereby increase their compliance. On week 3, participants again wore the actigraphs and Daysimeters (similar to week 1) and filled out the KSS and SVS questionnaires 4 times per day. 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.
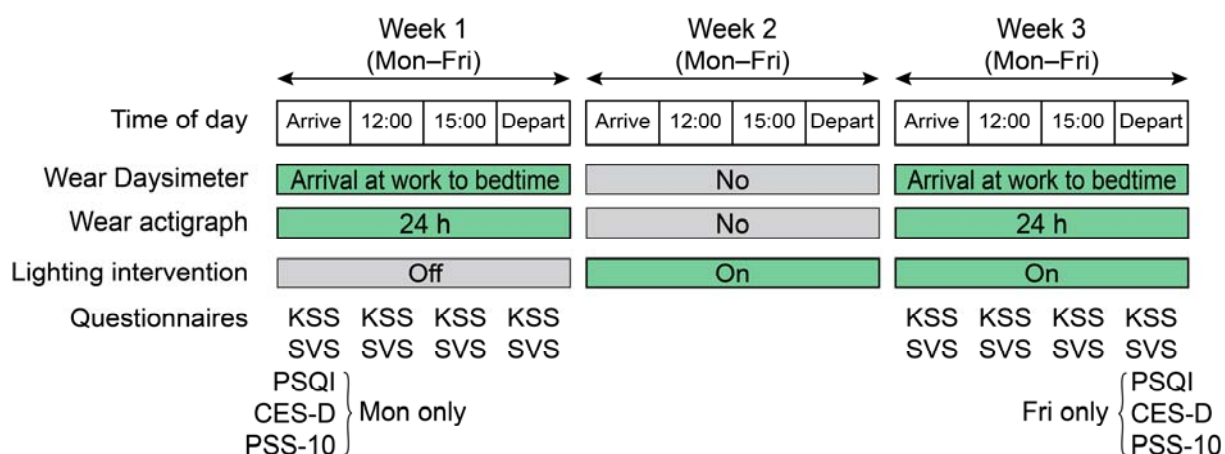

Figure 3 – The experimental protocol used in this study

2.5 Data Analysis

Data for all measures were analysed for statistical significance ($p < 0,05$) using post hoc, paired, 2-tailed Student's *t*-tests. With respect to the questionnaire data, day 1 scores were not included in the analyses due to the occurrence of the Columbus Day holiday (2017-10-09) during week 3 of the cohort 1 session; hence the questionnaire analysis included data obtained from days 2 to 5 for the baseline and intervention. Seventeen of 20 participants completed the questionnaires on at least 2 of the 4 days, and their data were included in the analyses. Given that questionnaire data were missing for various time points, the data for days 2-5 were averaged for each of the 4 times of day (arrival, 12:00, 15:00, and departure). Statistical analyses were performed on these averages. Data from 15 of 20 participants who wore the actigraphy device for at least 2 of the 4 days of each data collection period were included in the analyses.

3 Results

3.1 CS Exposures

The Daysimeter data confirmed that participants received significantly greater CS in the morning (0.27 ± 0.02), but not in the afternoon (0.16 ± 0.02), compared to baseline (0.15 ± 0.01 and 0.18 ± 0.02, respectively). The CS values recorded during the intervention were, on average, slightly lower than the targeted morning CS of 0,3, possibly because participants were not seated in front of their computers at all times. With respect to the baseline CS exposures, the lower levels experienced in the morning might be attributable to workers arriving to their offices later than 06:00, the occurrence of morning meetings, and/or less daylight/sunlight penetrating their workspaces. Figure 4 shows the mean ± standard error of the mean (SEM) morning and afternoon CS values.
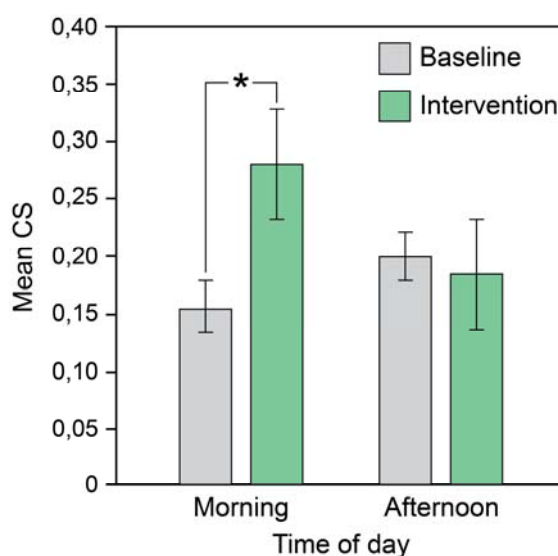

Figure 4 – Mean ± SEM CS values recorded by Daysimeter worn by the participants at baseline (week 1) and intervention (week 3). The asterisk denotes a statistically significant ($p < 0,05$) difference

3.2 Questionnaires

The questionnaire data showed that KSS scores were reduced significantly ($p = 0,04$) during the intervention week at 15:00 (Figure 5, Table 3). Although not statistically significant, sleepiness scores during the intervention were lower than during baseline at 12:00 and at departure. No statistically significant differences between the intervention and baseline were identified for the SVS measure at any time point (see Table 3).
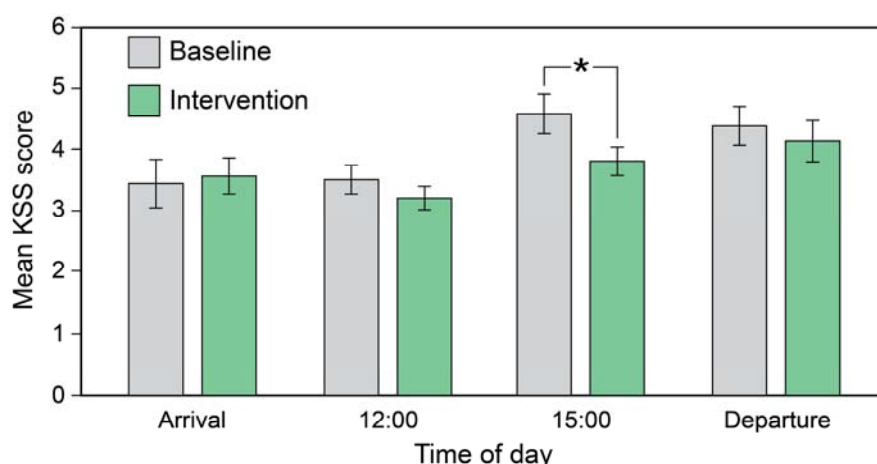
Figure 5 – Mean ± SEM KSS scores recorded by the participants at baseline (week 1) and intervention (week 3) by time of day. The asterisk denotes a statistically significant ($p < 0{,}05$) difference

Table 3 – Mean ± SEM KSS and SVS scores recorded by the participants at baseline (week 1) and intervention (week 3) for the 4 times of day. Lower KSS scores indicate less sleepiness and higher SVS scores indicate higher alertness, vitality, and energy

	Arrival	12:00	15:00	Departure
KSS				
Baseline	3,4 ± 0,22	3,5 ± 0,20	4,6 ± 0,22	4,4 ± 0,22
Intervention	3,6 ± 0,22	3,2 ± 0,13	3,8 ± 0,18	4,1 ± 0,22
p value	0,64	0,12	**0,04**	0,52
SVS				
Baseline	4,41 ± 0,34	4,48 ± 0,22	4,26 ± 0,21	4,14 ± 0,20
Intervention	4,45 ± 0,26	4,68 ± 0,26	4,51± 0,23	4,38 ± 0,21
p value	0,88	0,26	0,17	0,23

Note: Statistically significant ($p < 0{,}05$) difference is shown in bold

3.3 Actigraphy

As hypothesized, on average the morning blue lighting intervention advanced the timing of participants' sleep (Table 4). Participants fell asleep 8 min earlier and woke up 38 min earlier compared to baseline; however, only the difference in sleep end time was statistically significant ($p = 0{,}016$). Although not statistically significant, total sleep time was reduced by 16 min because the advance in sleep end time was greater than the advance in sleep start time. No other sleep measures were affected by the lighting interventions relative to baseline. Consistent with the hypothesis that the blue lighting intervention advanced circadian phase, activity acrophase (time of peak of activity in a 24-h cycle) was also advanced, but the difference was not statistically significant (Table 5). IS and IV also improved following the light intervention, but again the differences compared to baseline did not reach statistical significance (see Table 5).

Table 4 – Sleep outcome results based upon actigraphy

	Sleep start time (hh:mm)	Sleep end time (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
p value	0,60	**0,016**	0,42	0,31	0,30	0,21

Note: Statistically significant ($p < 0{,}05$) difference is shown in bold

Table 5 – Activity-related measures results at baseline and intervention (week 3)

	Mean interdaily stability (IS)	Mean intradaily variability (IV)	Activity acrophase (hh:mm:ss)
Baseline	0,65	0,98	10:06:02
Intervention	0,71	0,96	09:55:06
p value	0,22	0,82	0,77

4 Discussion

The study's findings are consistent with our a priori hypotheses. With respect to Hypothesis 1, high CS in the morning (06:00 to 12:00) from the blue lighting intervention, on average, appears to have advanced participants' circadian phase. Participants had earlier sleep start times (a difference of 8 min) and statistically significant earlier sleep end times (a difference of 22 min). An earlier activity acrophase, albeit not statistically significant, also indicates that the intervention advanced circadian phase (see Table 5). The human circadian system needs to advance by about 10-15 min daily to reset the biological clock. Consistently, the observed advances in sleep start and sleep end times suggest that the participants were collectively better entrained to the 24-h light dark cycle following the blue lighting intervention. Although the observed effects were small, it should be emphasized that the participants may already have been largely entrained to the local 24-h light-dark cycle. Thus, the modest advancing effect of the blue lighting intervention may simply reflect the limited potential that the intervention could have had with this population. Importantly, these findings are consistent with our basic understanding of light's impact on circadian phase.

As further support, the measures of circadian rhythms consolidation (IV and IS ratios) also suggest greater entrainment following the desktop lighting interventions. The IS ratio quantifies the extent to which all recorded 24-h activity profiles resemble each other and, thus, the higher mean IS value after the lighting interventions shows greater entrainment compared to baseline. The IV mean ratio, which quantifies the fragmentation of the rhythm, was also lower compared to baseline and indicates better entrainment. Although these differences in IV and IS were not statistically significant, these results are at least consistent with the inference that entrainment was improved.

Previous laboratory studies have shown that blue light can provide an alerting stimulus (Revell et al., 2006, Sahin et al., 2014), but the present results did not offer strong support for Hypothesis 2, whereby the morning blue lighting intervention would increase alertness as measured by KSS and SVS. The failure to support Hypothesis 2 and the inconsistency of the present findings with other literature is probably due to the participants' limited duration of exposure to the blue light before they completed the questionnaires upon arrival. By noon, there was a stronger, although not statistically significant, indication that the preceding lighting interventions (blue light and some white light) reduced subjective sleepiness and increased subjective vitality (see Table 3). The lowest levels of subjective sleepiness and highest levels of subjective vitality are seen during mid-day, so one would not expect major differences between baseline (week 1) and intervention (week 3). However, consistent with Hypothesis 3 and with published literature (Sahin and Figueiro, 2013, Sahin et al., 2014), the red lighting intervention in the afternoon near the post-lunch dip (i.e., around 15:00) significantly reduced subjective sleepiness and, although not statistically significant, increased subjective vitality.

Field studies are fraught with uncontrolled sources of experimental variability. For example, due to compliance issues resulting in missing data, we used the average data rather than the daily and hourly data. Although not as robust as results from more-controlled laboratory studies, the present findings from the field do not contradict our basic understanding of how light can affect non-visual pathways from the retina to the brain. Specifically, the present findings are consistent with the suggestion that tailored lighting interventions can help entrain building occupants and can increase alertness during working hours. The "non-visual layer of light" solution utilized in the present study (see Figure 1) may or may not be ideal, but it was nonetheless practical and inexpensive to implement while helping to reinforce the bridge between laboratory results and field applications.

Acknowledgements

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