Original article

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Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality

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Objectives Specifications and standards for lighting installations in occupational settings are based on the spectral sensitivity of the classical visual system and do not take into account the recently discovered melanopsin-based, blue-light-sensitive photoreceptive system. The authors investigated the effects of exposure to blue-enriched white light during daytime workhours in an office setting.

Methods The experiment was conducted on 104 white-collar workers on two office floors. After baseline assessments under existing lighting conditions, every participant was exposed to two new lighting conditions, each lasting 4 weeks. One consisted of blue-enriched white light (17 000 K) and the other of white light (4000 K). The order was balanced between the floors. Questionnaire and rating scales were used to assess alertness, mood, sleep quality, performance, mental effort, headache and eye strain, and mood throughout the 8-week intervention.

Results Altogether 94 participants [mean age 36.4 (SD 10.2) years] were included in the analysis. Compared with white light (4000 K), blue-enriched white light (17 000 K) improved the subjective measures of alertness (P<0.0001), positive mood (P=0.0001), performance (P<0.0001), evening fatigue (P=0.0001), irritability (P=0.004), concentration (P<0.0001), and eye discomfort (P=0.002). Daytime sleepiness was reduced (P=0.0001), and the quality of subjective nocturnal sleep (P=0.016) was improved under blue-enriched white light. When the participants' expectation about the effect of the light treatments was entered into the analysis as a covariate, significant effects persisted for performance, alertness, evening fatigue, irritability, difficulty focusing, concentrating, and blurred vision.

Conclusions Exposure to blue-enriched white light during daytime workhours improves subjective alertness, performance, and evening fatigue.

Key terms circadian rhythm; fatigue; melanopsin; mood; office lighting.

Specifications for lighting in occupational settings are based on the well-established visual effects of light, with aspects such as illuminance, glare restriction, and the color-rendering index being taken into account (1). However, during the past two decades evidence has accumulated in support of the claim that, in addition to facilitating vision, exposure to polychromatic white light has many "nonvisual" effects. These nonvisual effects include physiological responses such as the suppression of melatonin (2), circadian phase shifting (3), the elevation of core body temperature (4), and heart rate (5). Furthermore, exposure to polychromatic white light elicits behavioral responses, which include enhancing alertness and performance (6–9) and brain responses to cognitive tasks, as detected by photon emission tomography (10) and functional magnetic resonance imaging (fMRI) (11).

Nonvisual effects of light have been shown to be mediated, at least in part, by a recently discovered melanopsin-dependent photoreceptive system (12). Melanopsin is a photopigment found in intrinsically photosensitive retinal ganglion cells of the eye (13) and is the most sensitive to wavelengths of approximately 480 nm (14). As a consequence, the nonvisual effects produced through exposure to light are greater when the wavelengths are shorter than when the light is geared towards vision (15, 16). Exposure to blue light at night has been shown to have a greater effect on various physiological measures, such as melatonin suppression, alertness, thermoregulation, heart rate, cognitive performance and

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electroencephalographic dynamics, when compared with green light of the same intensity (17, 18).

Most laboratory studies have investigated the effects of light at night because melatonin suppression and circadian phase shifts, which were the first nonvisual effects to be studied, are the most responsive to light at night. However, exposure to bright white light during the daytime has also been shown to improve performance (19) and enhance brain responses in an attention task, as assessed by fMRI (11). Furthermore, recent fMRI studies have shown that daytime exposure to blue light, when compared with green (20) or violet (21) light, is more effective in enhancing responses to a memory task in several cortical, thalamic, and brainstem areas. These recent laboratory data suggest that increasing the contribution of short wavelengths to the spectral composition of light may also enhance alertness and performance in real-world settings.

We conducted a field trial to investigate the effects of blue-enriched white light using two light sources (17 000 and 4000 K). The 17 000 K light source was designed to optimize the activation of the melanopsin-based system, while, at the same time, not compromising visual functions.

The 17 000 K, blue-enriched white light used in this trial has previously been shown to improve subjective well-being, fatigue, alertness, and performance in a small study (22). Although the results of this pilot study were positive, it was difficult to draw any firm conclusions from it because, in the control condition, the effects were also positive. Furthermore, the control condition did not include the introduction of a novel light source, and control and intervention groups did not contain equal numbers of participants (22). In this paper, we report that exposure to blue-enriched white light in an occupational setting improves subjective measures of alertness, performance, positive emotions, and sleep quality without compromising visual functions.

Study population and methods

Study setting

This investigation took place between the 25th of January and the 20th of March 2007 at a distribution company for electronic parts located in northern England, at a latitude of 52 degrees north. Two floors (floors 3 and 4) of a large office building, which houses the company, were selected and used in the trial. Each floor was the same with regard to the layout of desks and the environmental light exposure. The two floors were also very similar with respect to the nature of the work carried out. The habitual start and end time of the work on both floors were 0830 and 1645, respectively. Sunrise varied from 0755 at the beginning of the study period to 0609 at its end; dusk varied from 1636 to 1813. Thus, for most of the study, dawn and dusk occurred outside the workhours, but the exposure to light during the workers' commute to and from work will have varied from the beginning to the end of the study.

Study design

A cross-over design study with a duration of 8 weeks was used. The workers on the first floor completed 4 weeks under blue-enriched white light followed by 4 weeks under white light, and the second group completed 4 weeks under white light followed by 4 weeks under blue-enriched white light. The baseline assessments were carried out under the existing lighting conditions in the week preceding the installation of the experimental light conditions. The change in the lighting conditions took place over the weekend. We decided to use a cross-over design rather than a parallel group design because the participants could not be assigned randomly to the interventions (or the order of the interventions); instead the assignment was based on their work location (ie, floor). Even though these floors were very similar with respect to lay-out, the composition of the workforce, the contribution of natural light, and the like, small differences between the floors may have existed. In a parallel design, an effect of intervention could not have been distinguished from an effect of floor or a differential impact of, for example, the changes in natural light exposure in the course of the study period on these two floors. The use of a cross-over design allowed for an assessment of the effects of intervention and floor.

Moreover, the cross-over design minimized the influence of interindividual differences in expectation in a study in which the participants were not blind to the condition.

Study population

Altogether 104 white-collar workers took part in the trial, which was favorably reviewed by the University of Surrey Ethics Committee. All of the participants gave their written informed consent prior to any study procedures. The participants were not informed of the expected outcome of the study. Ten participants withdrew from the study. The reasons for withdrawal included loss of interest in the study, change of floor during the study, and time off work during the study. The analyses presented in this report are therefore based on 94 participants.

Questionnaires

The participants completed a set of baseline questionnaires under existing lighting conditions. The baseline questionnaires consisted of a general demographics

questionnaire, the Pittsburgh Sleep Quality Index (PSQI) (23), and the Horne-Östberg (H-O) Questionnaire for diurnal preference (24). To estimate vitality, energy, activity, alertness, concentration, tiredness, and trouble thinking over the 3-day period prior to the completion of the questionnaires, we used a 7-point Likert scale called the Workplace Questionnaire. To estimate how daytime alertness and performance and evening fatigue changed over a 2-week period, we used a 9-point Likert scale called the Past Two Weeks Questionnaire. The questionnaires were completed on Tuesday.

During the two 4-week periods of exposure to experimental lighting conditions, the participants completed questionnaires in the morning, midday, and late afternoon on the Tuesday of every week. They were requested to complete the morning measures in the hour after their arrival at work and to consider only the time since their arrival at work. During the morning session, the Karolinska Sleep Diary (KSD) (25), a modified version of the Morning Need of Recovery Scale (26), the Karolinska Sleepiness Scale (KSS) (27), and the Rating Scale Mental Effort (RSME) (28) were completed. The KSS and RSME were repeated during the lunchtime session. The KSS assessed sleepiness during the past 10 minutes and the RSME questionnaire assessed effort needed for activities that had just been completed. The evening session consisted of the Headache and Eye Strain Scale (H&ES), the Positive and Negative Affect Scale (PANAS) (29), the KSS, and the RSME. The H&ES assessed current symptoms of eye strain and headache. In addition, on the first days after a lighting change, during the lunchtime session, a 7-point Likert-scale questionnaire was administered to probe the participants' expectations of the effect of the lighting change. In this expectation questionnaire, the participants were asked whether they expected the lighting to have any effect on their visual comfort, mood, performance, alertness, vitality, concentration, and sleep quality. To evaluate how the participants felt about the change in lighting (ie, from blue-enriched white light to white light or from white light to blue-enriched white light), we asked whether the participants noticed any difference in the lighting condition and whether the current situation was better or worse than the previous one. A 5-point Likert scale was used in which a score of 1 was associated with "much worse" and a score of 5 was associated with "much better". At the end of each 4-week period of light exposure, the PSQI, the Workplace Lighting Questionnaire, and the Past Two Weeks Questionnaire were administered.

Lighting

A newly developed fluorescent light source with a highly correlated color temperature (17 000 K, Philips master TL-D Activiva Active, Philips, Roozendaal, Netherlands) was compared with a similar light source with a lower color temperature (4000 K, Philips master TL-D super 80). Both types of fluorescent tubes were 18 W and had a similar spectral power distribution in the medium and long wavelength ranges (figure 1), but the 17 000 K light source produced more output between 420 to 480 nm.

Baseline assessments, which were used for reference, were made under lighting conditions that had been in place for some time. At the baseline, the light was provided by basic white halophosphate lamps with a horizontal average illuminance of 409.11 (SD 251.61) lx, the irradiance measures ranging from 1.32 to

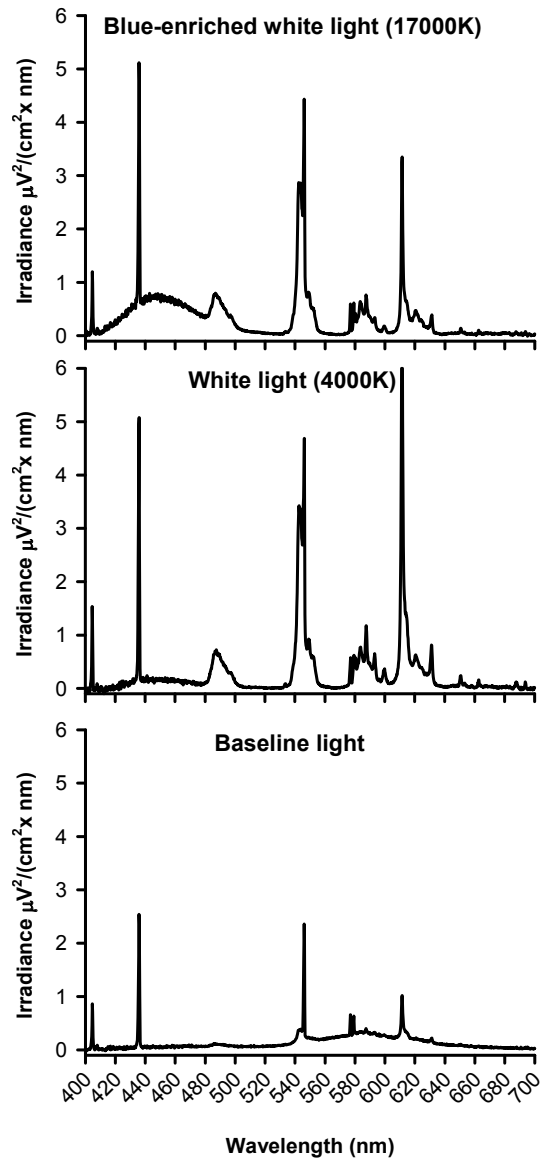

Figure 1. Spectral composition of the experimental blue-enriched white light (17 000 K, top panel) and white light (4000 K, middle panel) and the baseline (bottom panel) light conditions. The measurements were obtained in the center of the office area.

6.14×0^{14} μW/cm$^{2\cdot}$ at the work surface. The spectral composition of the baseline light was compared with the 4000 K and 17 000 K conditions, as shown in figure 1.

The mean illuminance levels measured on the work surfaces at several locations in the office were 310.35 (SD 98.90) lx and 421.07 (SD 128.55) lx for the blue-enriched white light and the white light, respectively. Irradiance was also measured, and it ranged from 2.58 to 6.42×10^{14} μW/cm^2 in the 17 000 K condition and from 2.4 to 4.49×10^{14} μW/cm^2 in the 4000 K condition. The contribution of artificial light to the total illuminance measured vertically (in the angle of gaze) and horizontally was estimated in several locations in the office. In the blue-enriched white-light condition, the contribution of artificial light represented a mean of 79.60 (SD 11.78)% and 68.04 (SD 26.63)% for the horizontal and vertical measurements, respectively. In the white-light condition, the contribution of artificial light averaged 79.40 (SD 12.64)% and 70.85 (SD 25.65)% for the horizontal and vertical measurements, respectively.

Statistical analysis

All of the statistical analyses were performed with SAS version 9.1 (SAS Institute, Cary, NC, USA). Comparisons of repeated measures were made between the light conditions using mixed-model analyses of variance for repeated measures (PROC Mixed). Baseline values formed the covariate in the analyses of the PSQI, Past Two Weeks Questionnaire, Workplace Questionnaire, and the KSD.

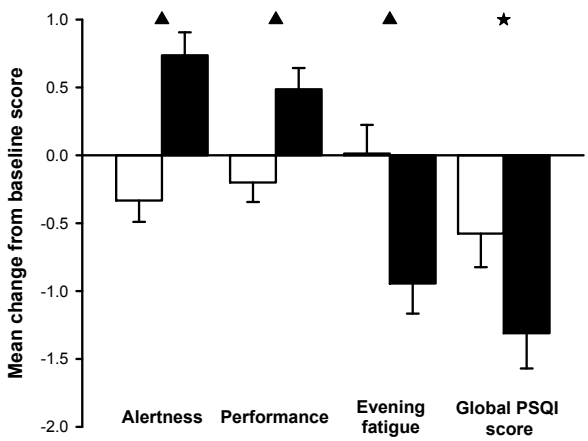

Figure 2. Effect of light on daytime alertness, self-rated performance, evening fatigue, and the global score of the Pittsburgh Sleep Quality Index (PSQI) in relation to the baseline condition. The data have been presented as the change in the means and standard errors of the means from the baseline. The units on the ordinate are those of the various scales. The minimum–maximum of these scales follow: 1–9 for alertness, 1–9 for self-rated performance, 1–9 for evening fatigue, and 0–21 for the PSQI. Note that a reduction in the PSQI indicates an improvement in overall sleep quality. P-values are given for the contrast between the white 4000 K (white bars) and blue-enriched 17 000 K (black bars) white light with the baseline as a covariate (* P<0.02, ▲ P<0.0001).

Condition (blue-enriched 17 000 K versus white 4000 K) and participant, as well as light exposure order, were factors in all of the analyses. Contrasts were assessed with the LSMEANS statement. All of the P-values were based on Kenward-Roger's corrected degrees of freedom (30). Unless stated otherwise, the reported P-values are for contrasts between the 4000 K and 17 000 K light conditions.

Results

The reported results are based on data from 94 participants on two floors, 52 on the first floor {26 women with a mean age of 34.9 [standard error of the mean (SE) 1.4] years} and 42 on the second [19 women with a mean age of 37.4 (SE 1.5) years].

An analysis of the baseline questionnaires showed no difference between the two floors prior to the switch to the experimental light conditions.

Assessment at the end of the 4-week periods

At the end of the 4-week periods, the blue-enriched white light condition (17 000 K) revealed an increase in alertness (P<0.0001) and performance (P<0.0001) and a decrease in evening fatigue (P=0.0001) when compared with the white light (4000 K) condition (figure 2). The participants also reported improved sleep quality, reflected in a decrease in the global PSQI score (P=0.016) and the PSQI sleep-quality component (P=0.02). All of these effects of condition were also significant when the analyses were completed without the baseline values being used as a covariate. Note that, when compared with the baseline values, the effects of blue-enriched white light were all positive and statistically significant. For the white light (4000 K) condition, a significant decline in alertness, but not in performance or evening fatigue, was observed when compared with the baseline values.

The analyses of the data from the Workplace Questionnaire, which was also administered at the end of the 4-week period, support these results. According to this questionnaire, exposure to blue-enriched white light, when compared with exposure to white light, improved how the participants felt during the past 3 days at work with respect to vitality (P=0.0008), activity (P=0.008), energy (P<0.0001), alertness (P<0.0008), the ability to concentrate (P=0.005) and the ability to think clearly (P<0.0001). The participants also reported that they felt less tired (P<0.0001).

The overall PSQI score and the scores for the seven components of the PSQI were compared for the two light conditions. For each of the seven components, a lower score indicates improvement. Thus a low sleep

duration score reflects an increase in sleep duration. The analyses, in which the baseline scores were used as a covariate, revealed an improvement in sleep after exposure to blue-enriched white light (17 000 K), when compared with the results of exposure to white light (4000 K). Thus the global PSQI scores were significantly improved (ie, lower) after exposure to blue-enriched white light (P=0.016), as were those for sleep quality (P=0.02), sleep duration (P=0.03), and daytime dysfunction (P=0.03) (table 1).

Weekly assessments

The analyses of the variables collected on the Tuesday of each week (table 2) revealed that, compared with white light (4000 K), blue-enriched white light (17 000 K) significantly decreased sleepiness, as assessed by the KSS. Blue-enriched white light also significantly reduced mental effort and increased positive mood, as assessed by the PANAS. Negative mood was not affected by the light condition. The incidence of irritability, eye strain, eye discomfort, eye fatigue, difficulty focusing, and difficulty concentrating and blurred vision (estimated by the 9-point Headache and Eye Strain Scale) were all significantly better with blue-enriched light (17 000 K) when compared with the corresponding results of the white light (4000 K) condition.

Table 2 illustrates that, in addition to the effects of light, for some of these variables, a significant effect of order, as well as a significant interaction between light and order, was observed. The effect of the factor "order" was significant for positive mood, and the interaction between

Table 1. Effect of the light exposure conditions on sleep, as assessed by the Pittsburgh Sleep Quality Index (PSQI). A higher score reflects a reduction in sleep quality, latency, duration, habitual efficiency, disturbance, medication, and dysfunction and an increase in sleep efficiency and time in bed. (SE = standard error of the mean)

	Baseline		Blue-enriched white light (17 000 K)		White light (4 000 K)		P-value
	Mean	SE	Mean	SE	Mean	SE	
PSQI (0–21) [a]	5.95	0.30	4.68	0.29	5.42	0.31	0.02
Sleep quality (0–3) [a]	1.02	0.06	0.93	0.07	1.12	0.08	0.02
Sleep latency (0–3) [a]	1.02	0.08	0.79	0.09	0.83	0.07	0.64
Sleep duration (0–3) [a]	0.86	0.07	0.65	0.06	0.76	0.06	0.03
Habitual sleep efficiency (0–3) [a]	0.57	0.09	0.32	0.07	0.43	0.08	0.17
Sleep disturbance (0–3) [a]	1.20	0.04	1.11	0.06	1.17	0.05	0.54
Use of sleep medication (0–3) [a]	0.13	0.05	0.10	0.06	0.18	0.07	0.32
Daytime dysfunction (0–3) [a]	1.02	0.07	0.77	0.07	0.93	0.08	0.03
Sleep efficiency [a]	0.86	0.04	0.91	0.01	0.92	0.04	0.77
Time in bed (minutes)	462.72	7.03	467.46	4.55	465.54	6.30	0.70

[a] The range of the scale is shown in parentheses.

Table 2. Effect of experimental light on mood, eye strain, headaches, mental effort, and sleepiness, as assessed by the Positive and Negative Effect Scale (PANAS), the Eye Strain and Headache Questionnaire, the Mental Effort Rating Scale, and the Karolinska Sleepiness Scale (KSS). (SE = standard error of the mean)

	Blue-enriched light (17 000 K)		White light (4000 K)		Analysis of variance		
	Mean	SE	Mean	SE	Light effect	Order effect	Light × order effect
Sleepiness [KSS, 1–9 (sleepy)]	3.60	0.13	4.04	0.12	0.0004	0.33	0.1
Mental effort [0–150 (extreme effort)]	23.67	1.49	26.20	1.65	0.015	0.39	0.003
PANAS [10–50 (extremely)]							
Positive mood	27.96	0.76	25.88	0.81	0.005	0.03	<0.0001
Negative mood	13.27	0.48	13.72	0.52	0.3	0.23	<0.0001
Headache and eye strain scale [1–4 (severe)]							
Irritability	1.43	0.05	1.62	0.06	0.004	0.57	0.46
Headache	1.32	0.04	1.40	0.05	0.17	0.18	0.8
Eye strain	1.54	0.05	1.76	0.07	0.005	0.23	0.95
Eyes discomfort	1.45	0.04	1.68	0.06	0.002	0.81	0.43
Eye fatigue	1.63	0.05	1.83	0.07	0.01	0.39	0.59
Difficulty focusing	1.21	0.04	1.45	0.05	<0.0001	0.12	0.99
Difficulty concentrating	1.37	0.04	1.65	0.06	<0.0001	0.18	0.91
Blurred vision	1.09	0.02	1.21	0.04	0.0005	0.7	0.35

the factors "light" and "order" was significant for mental effort and both positive mood and negative mood.

The temporal evolution of some of the treatment effects is shown in figure 3.

For many variables treatment effects were already present during the first week of the assessment (eg, positive mood, sleepiness, difficulty focusing). For others (eg, irritability, deep sleep), the treatment effect became significant during the last 2–3 weeks of exposure. A reduction of the effect over time was not observed for any of the variables.

All of the analyses were repeated to investigate whether age, gender, or diurnal preference (morningness or eveningness derived from the H-O score) interacted with the effect of light. None of these factors interacted significantly with the aforementioned effects of light.

Assessment at the beginning of the 4-week periods

To investigate whether the participants had any expectations about the effects of the different types of light, we analyzed the expectation questionnaire, which was completed on the second day of exposure to each light condition (ie, during week 1 and week 5). The participants were asked whether the current lighting condition was worse or better than the previous one.

In week 1, during which one floor changed from the baseline lighting condition to 4000 K light and the other floor changed from the baseline lighting condition to 17 000 K light, the mean rating was 3.47 (SD 1.16) (N=34) and 3.67 (SD 1.15) (N=30), respectively (30 = no opinion; P=0.50 for the difference between floors). In week 5, the participants rated the change from white light (4000 K) to blue-enriched white light (17 000 K) as better [mean 3.74 (SD 1.15), N=35] than the change from blue-enriched white light to white light [mean 2.68 (SD 1.13), N=41); 18 participants did not have an opinion. The difference between the rating of the blue-enriched to white-light transition differed significantly from the transition from white light to blue-enriched white light (P=0.0001).

The questionnaire also asked about the expectations for the effects of the light in relation to visual comfort, mood, performance, alertness, vitality, concentration, and sleep quality. The analysis of the expectations at the beginning of the first 4-week exposure period revealed that there were no differences in expectation with respect to the 4000 K and 17 000 K light. However, at the beginning of the second part of the study (week 5), the expectations differed significantly between the two light conditions for all of the indices, such that the expectations of the 17 000 K condition were more positive than those of the 4000 K for sleep quality (P=0.001), alertness (P<0.0001), performance (P<0.0001), visual comfort (P=0.005), mood (P=0.0003), vitality (P<0.00001), and concentration (P<0.00001). When we included

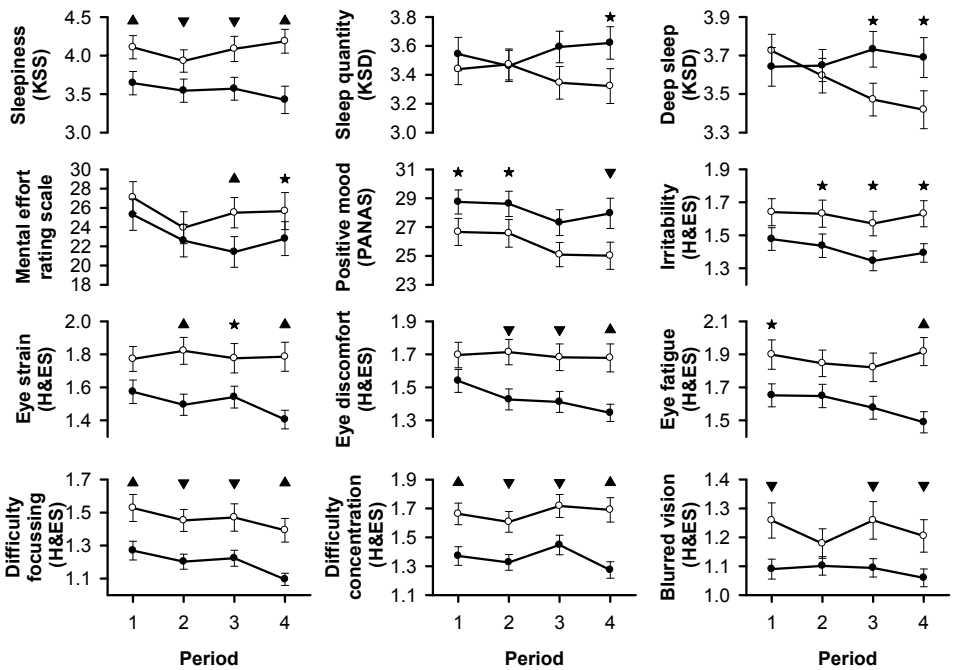

Figure 3. Effects of light intervention in the course of the 4-week intervention. The data points are the means and standard errors of the means for the Positive and Negative Affect Scale (PANAS), the Karolinska Sleepiness Scale (KSS), the Karolinska Sleep Diary (KSD), the Rating Scale Mental Effort (RSME), and the Headache and Eye Strain Scale (H&ES). Each period included all of the participants from both floors under blue-enriched white 17 000 K (filled symbols) and white 4000 K (unfilled symbols) light across the study (ie, the value for period 1 under the 17 000 K condition is based on the data collected during week 1 for floor 3 and week 5 for floor 4 (* P<0.05, ▼ P<0.01, ▲ P<0.001).

expectation as a covariate in the analysis, significant effects of light intervention persisted for performance, alertness, fatigue in the evening, the KSD question 10 (How much did you dream?), irritability, difficulty focusing, difficulty concentrating, and blurred vision. In addition, the response to question 7 (Did you have difficulties falling asleep?) of the KSD became significant. In this analysis the effects of light intervention were no longer significant for positive mood, eye strain, general eye discomfort, eye fatigue, mental effort, sleepiness, and the global PSQI score, as well as the PSQI sleep-quality component.

Discussion

The data show that blue-enriched white lighting in offices, when compared with white office lighting, has beneficial effects on daytime alertness, performance, mood, and eye strain, as well as on nighttime sleep quality and duration. The data are unlikely to be explained by a simple novelty effect because the control condition consisted of exposure to a new light source without an increased contribution of short-wavelength light. The data are also unlikely to be explained by an order effect, or a seasonal effect, because a cross-over design was used in the study. The data are consistent with the notion that current artificial light sources are suboptimal for supporting melanopsin-based nonvisual effects of light because wavelengths targeting this photoreceptive system are not well represented.

Traditionally, the effects of light on performance and sleepiness have been investigated at night or in night-shift settings (31–34) because it is in such settings that the circadian system is the most sensitive to light. The current data, obtained in a field study, add to the growing evidence that light can enhance positive mood and performance during the daytime. These data demonstrate that blue-enriched white light has the ability to improve self-reported measures of alertness, performance, and fatigue after daytime exposure to blue-enriched white light in a "real-life" setting for people who work normal office hours without any abnormal sleep–wake schedule being imposed.

The current data are consistent with those of a pilot study in which it was shown that 17 000 K, blue-enriched white light can improve subjective well-being, fatigue, alertness, and performance (22). The protocol utilized in our study included a larger number of participants. The balanced cross-over design ensured that all of the participants experienced a change in lighting conditions after the baseline assessments were carried out, while, at the same time, controlling for order and expectation effects. Whereas the effect of light was robust against order effects, order effects were observed.

The analysis of the "expectation" questionnaire showed that, at the beginning of the trial, the participants did not have different expectations with respect to the two light sources. However, after the first 4 weeks of the study, the expectations for blue-enriched white light were much more positive. This finding strongly suggests that the expectation effect was not related to positive expectations with respect to blue-enriched light, which could have been inadvertently conveyed during the prestudy information session. During a debriefing session after the study, the participants indicated that the change in expectation was caused by positive reports from the participants who had been exposed to blue-enriched white light during the first 4 weeks. Thus the overall effects of blue-enriched white light cannot be explained by an expectation effect, but a shift in expectation may have contributed to the order effect. The implication of this possibility is that it can be expected that, for exposures to blue-enriched white light that are longer in duration, the positive effects are unlikely to diminish over time. These order effects may also have contributed to the reduction of alertness below the baseline values for the 4000 K condition. For the floor that was first exposed to 17 000 K light, alertness during the subsequent 4000 K condition was significantly lower than the baseline value, whereas this was not the case for the other floor. Our interpretation of this finding is that, after first having been exposed to 17 000 K, 4000 K was "disliked" by the participants, and therefore the ratings fell below the baseline values.

The cross-over design and the conduct of the study during the winter months (January to March 2007) minimized the confounding effect of the lengthening of the natural photoperiod, which, in a previous study, was hypothesized to have been the cause of improved alertness and performance in the control group, which had no change in lighting conditions. That the seasonal effects did not contribute significantly to the effects of the light condition observed in our current experiment is also supported by the lack of a significant effect of the factor "period" for alertness (P=0.12), performance (P=0.43), fatigue in the evening (P=0.14), and PSQI (P=0.08).

The timing and location of the trial also ensured that the contribution of artificial light to the total light exposure was substantial. Conducting trials in situations with different daylight contributions (in different architectural style buildings, during other seasons, and at different latitudes) may further clarify the conditions under which the introduction of blue-enriched white light is beneficial.

Assessments were made in the current experiment using validated questionnaires and scales for sleepiness, alertness, mood, headache, eye strain, effort, and sleep quality. Blue-enriched white light had positive and

statistically significant effects on all of these domains. The magnitudes of the effects were also considerable. For example, sleepiness, as assessed by the KSS, differed by as much as 0.4 points between the conditions (on a 9-point scale). Positive mood was improved by 2 points, as assessed by the PANAS.

Some domains were assessed by several scales. For example, alertness was assessed by the Past Two Weeks Questionnaire and the Workplace Questionnaire. Sleepiness was assessed by the KSS and Workplace Questionnaire. Both assessments demonstrated the same positive effect.

Exposure to blue-enriched white light did not compromise visual functions. On the contrary, it appeared to be associated with a reduction in eye strain, discomfort, fatigue, and blurred vision. These findings indicate improved visual comfort when a person works under blue-enriched white light. This improved visual comfort may be related to the impact of the melanopsin system on the visual system. For example, it has recently been demonstrated that human and macaque pupil responses are driven by retinal ganglion cells that contain melanopsin and their spectral tuning (35). Thus exposure to blue-enriched white light may strongly result in stronger pupil constriction as compared with exposure to standard white light, which in turn may have contributed to the improvements in visual comfort that we observed with blue-enriched white light.

The positive effects of blue-enriched white light were not limited to the daytime. The need for a recovery scale that has previously been shown to be a good indicator of occupationally induced fatigue and health complaints (36) probes self-perceived function outside workhours. The effects of blue-enriched white light on this domain of waking function were positive.

A somewhat surprising finding in our study was the positive effects of blue-enriched white light on sleep quality and sleep duration. This effect was, however, present for both the PSQI and the KSD. Previously, positive effects of nighttime light exposure on daytime sleep have been reported (32) The positive effect of blue-enriched white light on sleep contrasts with the negative effects on sleep that have been reported with other alertness and performance-enhancing interventions such as caffeine (37).

The analysis of the covariance of age, H–Ö (morningness–eveningness), and gender revealed that diurnal preference, age, and gender did not significantly modulate the effect of blue-enriched white light.

The new source of blue-enriched white light was well liked by the participants, as indicated by their preference for the change from white to blue-enriched white light.

The mechanism by which blue-enriched white light exerts its nonvisual effects probably involves melanopsin-expressing ganglion cells. The nonvisual responses are thought to be mediated by projections from the melanopsin-expressing ganglion cells of the retina to the hypothalamus, brain stem, thalamus, and many other brain areas containing key structures in the regulation of sleepiness, attention, and working memory. The functional brain architecture of these responses is now emerging (10, 11, 20, 21). It should be noted that there is now also a substantial body of evidence showing that the inputs of rods and cones to these melanopsin-expressing ganglion cells contribute to nonvisual responses (38). This finding implies that wavelengths that target the three-cone system (420, 530, and 560 nm) may also play a role in the nonvisual functions of light.

Whereas the daytime effects of blue-enriched white light can be readily understood within a framework of the alerting and activating direct effects of light, the effects on nocturnal sleep need further explanation. These effects on sleep may be a consequence of improved daytime function and activity. Alternatively, they may reflect long-term effects of exposure to blue-enriched white light on the amplitude of the circadian-timing system. It has been previously shown that the amplitude of nocturnal melatonin secretion is significantly greater after daytime exposure to bright light than with exposure to dim light (39). Such a mechanism could very well explain the current sleep quality data because melatonin is known to have sleep-promoting properties (40, 41). In addition, it has been shown that increased illumination is able to improve rest–activity rhythms in several populations, such as the elderly (42) and those with dementia (43). Interestingly, the magnitude of the increase in melatonin secretion in an elderly population paralleled the improvement in sleep (42). It is possible that daytime exposure to blue-enriched white light in our sample enhanced the participants' nocturnal melatonin secretion and thereby improved sleep quality, which in turn resulted or contributed to enhanced daytime alertness and performance.

We have shown, through the use of a robust study design, that exposure to blue-enriched white light can improve alertness, performance, and mood in the workplace, as well as perceived functioning outside workhours and sleep quality. The data imply that waking functioning, visual comfort, and sleep quality can be improved by enriching the spectral composition of light sources with short wavelengths.

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