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Light exposure via a head-mounted device suppresses melatonin and improves vigilant attention without affecting cortisol and comfort

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Abstract: We aimed at assessing whether a head-mounted light therapy device, enriched in blue wavelengths, suppresses melatonin secretion and improves vigilant attention in the late evening hours. We also assessed whether using such light device is associated with discomfort and physiological stress. Seventeen healthy young participants (eight females) participated in a counterbalanced within-subject design during which they were exposed for 2 hr before habitual sleep time to a blue-enriched light (1500 lx) or to a lower intensity red-light (150 lx) control condition, using a new-generation light emitting diode (LED) head-mounted device. Compared to the red light control condition, blue-enriched light significantly reduced melatonin secretion and reaction times during a psychomotor vigilance task while no significant differences were detected in discomfort and cortisol levels. These results suggest that, compared to a control condition, blue-enriched light, delivered by a new-generation head-mounted device, elicits typical non-visual responses to light without detectable discomfort and physiological stress. They suggest that such devices might constitute an effective alternative to standard light boxes.

The circadian clock reflects an internal-based time-keeping system, generating rhythms with a periodicity of approximately 24 hr. The master clock of this time-keeping system is located in the suprachiasmatic nuclei of the hypothalamus and is heavily implicated in the temporal modulation of sleep and wakefulness, but also melatonin secretion, thermoregulation, pupil size, and cognition (Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Chellappa et al., 2011; Duffy, Kronauer, & Czeisler, 1996; Gaggioni, Maquet, Schmidt,

Dijk, & Vandewalle, 2014; Lockley et al., 2006). Cognitive performance has been shown to present circadian rhythmicity, the amplitude and, putatively, also the phase of which depend on the investigated cognitive domain (Schmidt, Collette, Cajochen, & Peigneux, 2007). Clock-induced adaptive arousal mechanisms are timed to achieve a continuous period of wakefulness during daytime and promote sleep during nighttime (Borbély, 1982; Daan, Beersma, & Borbély, 1984; Dijk & von Schantz, 2005). Accordingly,

circadian-driven troughs in cognitive performance are classically observed towards the end of the biological night (Schmidt et al., 2007).

Besides its central role for vision, the eye also perceives light to regulate numerous non-visual responses, such as the entrainment of the clock to the 24-hr light–dark cycle. To do so, light information is absorbed by photoreceptors at the level of the retina and is directly transmitted to the brain via the retinohypothalamic tract (LeGates, Fernandez, & Hattar, 2014).

Because of its potent effect on the circadian system, light therapy devices are used to phase shift circadian rhythmicity to better adapt to night shift work or transmeridian travel (Burgess & Emens, 2016; Crowley & Eastman, 2015). These light therapy devices were initially designed to treat seasonal affective disorder (SAD), for which they are the treatment of choice (Pail et al., 2011). The antidepressant effect of light therapy in SAD seems to rely in part on circadian re-entrainment (Lewy, Lefler, Emens, & Bauer, 2006).

Notably, besides its phase-shifting properties, light has also been shown to acutely affect physiology and behavior. Thus, light not only resets the phase of melatonin rhythms, but also leads to melatonin suppression during exposure. Finally, light has also been shown to present alerting effects and can enhance performance in several cognitive domains, such as vigilant attention, working memory, executive function, or declarative word-pair learning (Cajochen et al., 2011; Chellappa et al., 2012; Lockley et al., 2006; Vandewalle et al., 2007; Wright & Lack, 2001). Interestingly, it has been suggested that the antidepressant effect of light therapy in SAD also potentially relies on its ability to suppress melatonin secretion at night or to increase alertness and attention (Pail et al., 2011).

Most, if not all, non-visual responses to light in humans are more pronounced using monochromatic blue light or using blue-enriched polychromatic light (Brainard et al., 2001; Chellappa et al., 2012; Lockley et al., 2006; Vandewalle et al., 2007; Wright & Lack, 2001). This blue-shifted sensitivity is likely due to the implication of intrinsically photosensitive retinal ganglion cells, which express the blue-sensitive photopigment melanopsin (Gaggioni et al., 2014; LeGates et al., 2014). It is also probably because of these intrinsically photosensitive retinal ganglion cells that lower intensity blue-enriched light therapy has been reported to be as efficient as standard bright white light exposure for treating SAD (Anderson, Glod, Dai, Cao, & Lockley, 2009; Gordijn, 't Mannetje, & Meesters, 2012).

Light therapy is receiving growing interest as a potential efficient means to treat an increasing number of disorders or disabilities, including, for instance, non-seasonal major depression (Lam et al., 2016), depression during pregnancy (Bais et al., 2016), post-partum depression, bipolar depression or eating disorders (Terman, 2007), as well as sleep and circadian rhythm disorders (Geerdink, Walbeek, Beersma, Hommes, & Gordijn, 2016; van Maanen, Meijer, van der Heijden, & Oort, 2016), addiction (Siporin, 2014), sleep troubles in dementia (Ooms & Ju, 2016), and Parkinson's disease (Videnovic et al., 2017).

The most common light therapy devices consist of light boxes in front of which one has to sit for a given period of time (Pail et al., 2011). This may represent a major constraint such that an important challenge of light therapy is maintaining compliance (Dawson & Campbell, 1990; Pail et al., 2011). Other approaches have been developed, including constant changes in ceiling light delivery (Riemersma-van der Lek et al., 2008; Viola, James, Schlangen, & Dijk, 2008) or head-mounted devices (Lovato & Lack, 2016; Stewart et al., 1990). The latter allows for portable individualized light therapy and may represent an interesting alternative that increases compliance, since one can partly continue one's daily activities during light administration. The efficacy of head-mounted devices remains, however, unclear, with positive (Clark, Schocket, Turner, & Rosenthal, 1997; Stewart et al., 1990) but also many ambiguous (Levitt, Wesson, Joffe, Maunder, & King, 1996; Rosenthal et al., 1993; Teicher et al., 1995) treatment outcomes for SAD. Likewise, evidence suggesting that head-mounted light therapy devices affect melatonin secretion and circadian entrainment remain scarce (Boulos et al., 2002; Lovato & Lack, 2016; Paul et al., 2007; Wright, Lack, & Kennaway, 2004; Wright, Lack, & Partridge, 2001). Blue-green light administration through a head-mounted LED device (2000 lx) was shown to shift circadian phase and suppress melatonin secretion to a greater extent than a white light head-mounted LED device or a standard white light box of the same illuminance (Lovato & Lack, 2016; Wright et al., 2001).

First-generation head-mounted devices have been reported to induce discomfort and to impair performance on a psychomotor vigilance task (Paul et al., 2007, 2015). However, newer-generation head-mounted devices are being developed. They use blue-enriched light of lower intensities (< 2000 lx; Lovato & Lack, 2016; Slama, Deliens, Schmitz, Peigneux, & Leproult, 2015) than

previous devices (> 8000 lx; Paul et al., 2007) such that they might induce less discomfort and stress.

Here, we aimed at assessing whether a type of new-generation head-mounted light therapy device (Luminettes), enriched in blue wavelengths, was able to suppress melatonin secretion and to improve alertness and vigilant attention in the late evening, coinciding with melatonin onset. We also evaluated whether such a light device induces discomfort and physiological stress, assessed via salivary cortisol levels.

Materials and methods

The study was approved by the ethics committee of the University of Liège and performed according to the Declaration of Helsinki. All participants gave written informed consent before participation.

Seventeen healthy young volunteers participated in the study (see Table 1 for demographics). All participants were unmedicated and indicated good subjective sleep quality (Pittsburgh Sleep Quality Index ≤ 5; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) and no symptoms of major clinical depression (Beck Depression Inventory < 15; Steer, Ball, Ranieri, & Beck, 1997) or anxiety (Beck Anxiety Inventory < 16; Steer, Ranieri, Beck, & Clark, 1993). Extreme chronotypes (score < 21 or > 70 on the Morningness–Eveningness Questionnaire [Horne & Ostberg, 1976]) were excluded from the study since the latter have been suggested to differ in the phase relationship between the circadian timing system and sleep timing (e.g., Mongrain, Carrier, & Dumont, 2006). One week before starting the laboratory part, participants kept a fixed sleep–wake cycle for 7 days to ensure sufficient sleep and stable circadian entrainment before starting with the experimental protocol. Scheduled sleep–wake times were derived from an interview with the participants, taking into account their preferred sleep–wake habits and

professional duties. Compliance to the regimen was verified by means of actigraphic recordings. Actimetry-derived sleep and wake-up times did not differ between the experimental conditions (Table 1). Participants were instructed to abstain from alcohol and caffeine during 3 days preceding each study entrance.

The laboratory part comprised two conditions, separated by at least 1 week and implemented as a within-subject, pseudo-randomized, crossover design. At each visit, participants entered the laboratory 7 hr before usual bedtime. As depicted in Figure 1, they were kept under dim light conditions (< 5 lx) for 5 hr before being exposed for 2 hr to a bright blue-enriched light (1500 lx corneal level) or to a red light control condition (150 lx at corneal level). Light was delivered using an LED head-mounted portable device that includes a patented holographic surface reflecting light toward the lower retina such that sight is not hindered (Luminettes, Lucimed, Villers-Le-Bouillet, Belgium).

Photopic light stimulation was measured with a lux meter (Q203 Radiometer, Macam Photometrics, Livingston, UK). Light spectra were provided by the manufacturer (Figure 1). Estimation of spectrally weighted irradiance for the different retinal photoreceptors showed that all photoreceptor types (rods, melanopsin, and S/M/L-cones) were differently stimulated by each light condition (Table 2) preventing any inferences on the photoreceptors contributing to the differential impact of both light conditions.

Participants were kept under dim light (< 5 lx) for 1.5 hr following light exposure prior to leaving the lab, entailing a wake extension of 1.5 hr with respect to habitual sleep time. Participants were not allowed to stand up except for scheduled bathroom visits. Social interaction was restricted to communications with research staff. Saliva samples were collected at hourly intervals up to light administration and at half-hour intervals thereafter to assay melatonin and cortisol levels. The samples were analyzed by LCMS/MS

Table 1

Demographic data, questionnaire scores, and actimetry data (means and standard deviations)

Sample characteristics			
N (female/male)	17 (8/9)		
Age (years)	22.8 (1.8)		
Educational level (years)	14.26 (1.09)		
Self-reported sleep quality (PSQI)	3.58 (1.17)		
Chronotype (MEQ)	50.94 (7.93)		
	Blue light	**Red light**	*p*-values
Daytime propensity to fall asleep (ESS)	7.47 (4.28)	6.47 (3.35)	.167
Actimetry-derived wake-up time (hh:mm)	08:04 (38 min)	08:13 (43 min)	.536
Actimetry-derived sleep time (hh:mm)	23:51 (55 min)	23:56 (53 min)	.453

Note. PSQI = Pittsburgh Sleep Quality Index; MEQ = Morningness–Eveningness Questionnaire; ESS = Epworth Sleepiness Scale.
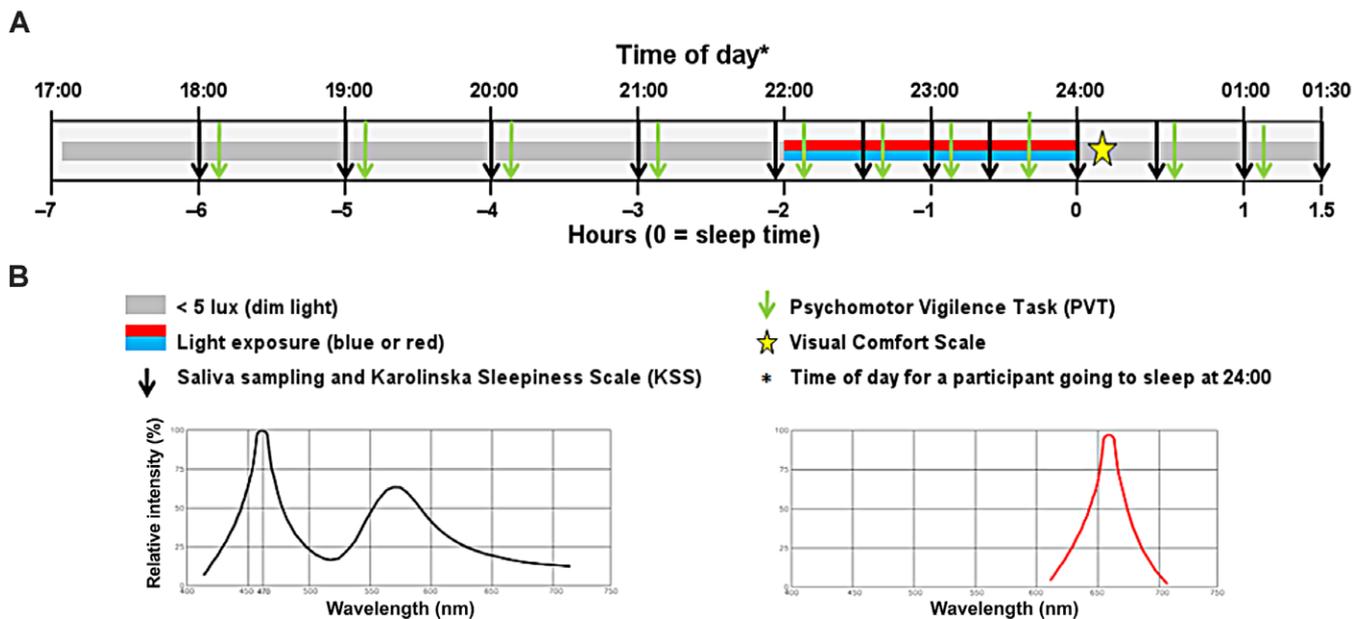
Figure 1. Schematic illustration of the (A) experimental design and (B) light spectra.

Table 2

Light characteristics (see also Figure 1)

	Blue light	Red light
Peak wavelength (nm)	460	660
Photopic illuminance (lx)	1500	150
Irradiance (μW/cm^2)	466	275
Photon flux (ph/cm^{2}s)	1.3×10^{15}	9.1×10^{14}
Spectrally weighted irradiance:		
Cyanopic (S-cone) stimulation	76.7	0
Melanopic stimulation	142.4	0.02
Rhodopic stimulation	177.8	0.18
Chloropic (M-cone) stimulation	228.5	4.9
Erythro (L-cone) stimulation	251.5	35.4

(TQ5500, Sciex, Framingham, MA, United States) for cortisol (limit of quantification: 0.1 μg/L, analytical coefficient of variation < 8.1%) and by a direct double-antibody radio-immunoassay kit (Buhlmann, Schönenbuch, Switzerland) for melatonin (limit of quantification: 0.9 pg/ml, analytical coefficient of variation < 16.7%).

Concomitant to the collection of saliva samples, subjective sleepiness was assessed by the Karolinska Sleepiness Scale (Åkerstedt & Gillberg, 1990). Furthermore, neurobehavioral performance was assessed by a modified version of the Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985). The PVT was administered at 10 occasions (four pre-, four during, and two post-light exposure). During the 5-min PVT, participants were instructed to press a response button as fast as possible as soon as a millisecond counter appeared on the computer screen, which was displayed at random intervals with an interstimulus interval of 2–10 s.

Feedback was provided by displaying the reaction time (RT) for 1 s. The dependent variables were median RTs, the mean of the 10% of fastest and slowest RTs, respectively, as well as the number of lapses (RT > 500 ms, transformed by $\sqrt{x} + \sqrt{x + 1}$ to stabilize variances according to Basner & Dinges, 2011).

Upon arrival, participants filled in the Epworth Sleepiness Scale (Johns, 1991), which quantifies self-reported propensity to fall asleep during daytime. Finally, immediately after post-light exposure, participants had to judge the light environment on different scales. Five questions evaluated general pleasure, clarity, light color, vigilance, and concentration on a 5-point Likert scale. Visual comfort was assessed on a scale from 1 (*highly uncomfortable*) to 10 (*highly comfortable*).

Statistical analyses were performed with SAS 9.3 (SAS Institute, Cary, NC, United States). We used a general linear mixed model with PROC MIXED to determine the effects of light condition (blue vs. red), session (12 time points for subjective sleepiness, melatonin, and cortisol levels and 10 time points for PVT performance), and the light condition × session interaction, with the subject effect as random factor. We also examined the effects of pre-, during-, and post-light exposure as a repeated effect. All repeated measures included a first-order autoregressive variance–covariance matrix being specified. Contrasts were calculated with the LSMEANS statement. Degrees of freedom of all *p*-values ware based on Kenward–Roger

approximation for linear mixed models. The *p*-values of multiple post hoc comparisons (two-tailed) were Tukey-adjusted. Visual comfort scales were compared between light conditions by using the non-parametric Wilcoxon test. For vigilance and subjective sleepiness, a final analysis accounted for potential baseline differences by dividing the collected values by the mean of the four sessions during pre-light exposure.

Results

Salivary melatonin and cortisol

Besides a main effect of time, $F(11, 312) = 21.32$, $p < .0001$, and of light condition, $F(1, 312) = 12.68$, $p < .0005$, a significant light condition × session interaction, $F(11, 312) = 2.81$, $p < .005$, was observed for salivary melatonin levels. As depicted in Figure 2A, melatonin levels did not differ between conditions before light exposure, while they were significantly reduced in response to blue-enriched light ($p < .05$ for light condition comparisons for sessions −1 to 0.5 hr relative to habitual bed time). Similarly, when averaging the sessions according to their occurrence with respect to the light exposure (pre-, during, and post-; Figure 2, right panel), an interaction between time bin and light condition was observed, $F(2, 316) = 3.67$; $p < .05$, with post hoc comparisons revealing that melatonin levels differed during and post- (all *p*s < .05) but not pre-light exposure ($p > .05$). Finally, analyses of individual melatonin secretion area under the curve (AUC) during the 2-hr light period indicated that AUC was lower under blue (AUC = 15.4 ± 16.12 pg/ml) compared to red (AUC = 25.35 ± 12.16 pg/ml) light exposure (T = −1.97, $p = .05$).

For cortisol levels, a main effect of time, $F(11, 312) = 7.02$, $p < .0001$, was detected, while neither the main effect of light condition, $F(1, 312) = 0.04$, $p > .5$, nor its interaction with the factor time, $F(11, 312) = .62$, $p > .5$, reached significance. Likewise, the light condition × time bin (pre-, during, post-) interaction did not reach significance, $F(2, 371) = 0.66$, $p > .5$.

Vigilant attention

Performance on the PVT was assessed by computing median RTs, means of the 10% of fastest and slowest RTs, respectively, as well as the number of attentional lapses (i.e., number of events with an RT > 500 ms). A main effect of time was observed for all dependent variables
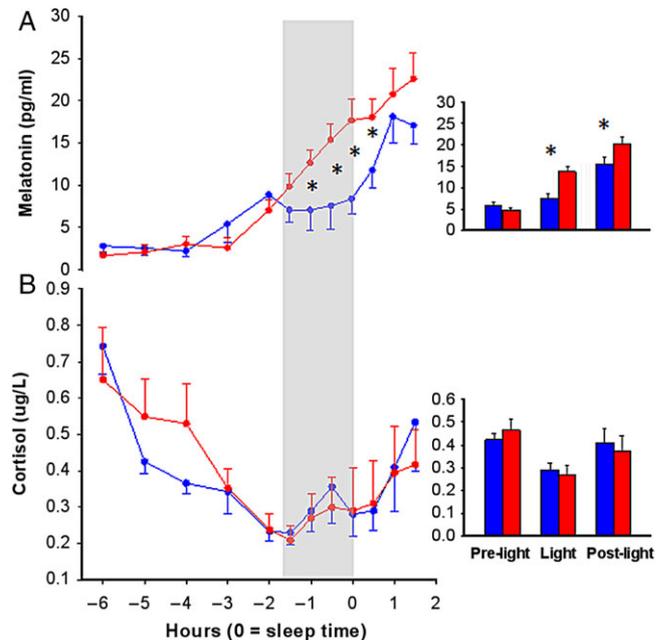
Figure 2. Time courses of (A) salivary melatonin and (B) cortisol levels (means and standard errors; left panel) and averaged with respect to their occurrence according to light exposure (right panel). The grey bar indicates the timing of light exposure. The *X*-axis of the left panel reflects time in hours, relative to habitual sleep time. Red = red light condition, blue = blue light condition. *$p_{corr} < .05$.

(Figure 3), such that RTs and the number of lapses increased with time into protocol: $F(9, 302) = 9.22$, $p < .0001$ for fast RTs; $F(9, 302) = 12.47$, $p < .0001$ for median RTs; $F(9, 302) = 9.35$, $p < .0001$ for slow RTs; and $F(9, 302) = 6.02$, $p < .005$ for lapses. Furthermore, a main effect of condition was detected with lower vigilance levels during the red compared to the blue light condition: $F(1, 302) = 3.70$, $p = .0552$ for lapses; $F(1, 302) = 22.14$, $p < .0001$ for fast RTs; $F(1, 302) = 5.25$, $p < .05$ for slow RTs; and $F(1, 302) = 14.51$, $p < .0001$ for median RTs. A significant interaction between light condition and time into protocol was detected for attentional lapses, $F(9, 302) = 2.30$, $p < .05$. When grouping the sessions according to their occurrence with respect to the light exposure (pre-, during, and post-; Figure 3, right panel), a significant interaction between time bin and light condition was observed for lapses, $F(2, 316) = 3.67$, $p < .05$, and median RTs, $F(2, 316) = 4.54$, $p < .05$. Performance did not significantly differ pre-light exposure, but was improved both during and post- (for lapses) or only post- (for median and fast RTs) blue-light exposure compared to red light exposure. Finally, when normalizing performance to the mean performance of the four sessions preceding
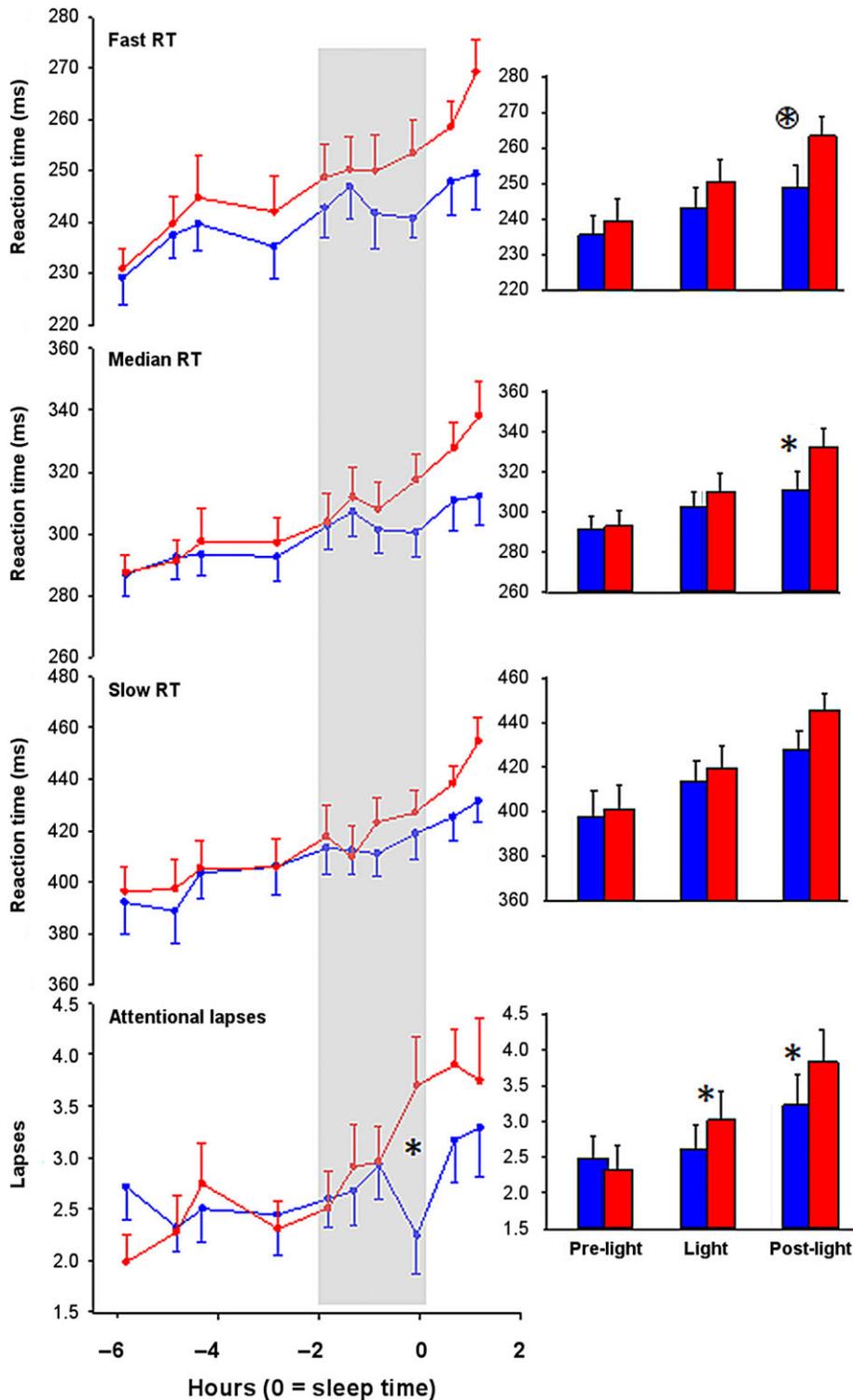
Figure 3. Time courses of different Psychomotor Vigilance Task (PVT) metrics (left panel) and averaged with respect to their occurrence according to light exposure (right panel). The grey bar indicates the timing of light exposure. The X-axis reflects time in hours, relative to habitual sleep time. *p_{corr} < .05. Circled *p_{corr} < .1. Red = red light condition; blue = blue light condition. RT = reaction time.

light exposure, we observed a main effect of time for all PVT measures—$F(9, 268) = 3.52$, $p < .004$ for lapses; $F(9, 286) = 9.38$, $p < .0001$ for slow RTs; $F(9, 268) = 15.39$, $p < .0001$ for median RTs; and $F(9, 298) = 11.39$, $p < .0001$ for fast RTs—but no main effect of the light condition (all ps > .05), while a significant time × light condition interaction was observed for median RTs, $F(9, 297) = 2.21$, $p < .05$.

Figure 4. Time course of subjective sleepiness scores (left panel) and averaged with respect to their occurrence according to light exposure (right panel). The grey bar indicates the timing of light exposure. The *X*-axis reflects time in hours, relative to habitual sleep time. Red = red light condition; blue = blue light condition. KSS = Karolinska Sleepiness Scale.
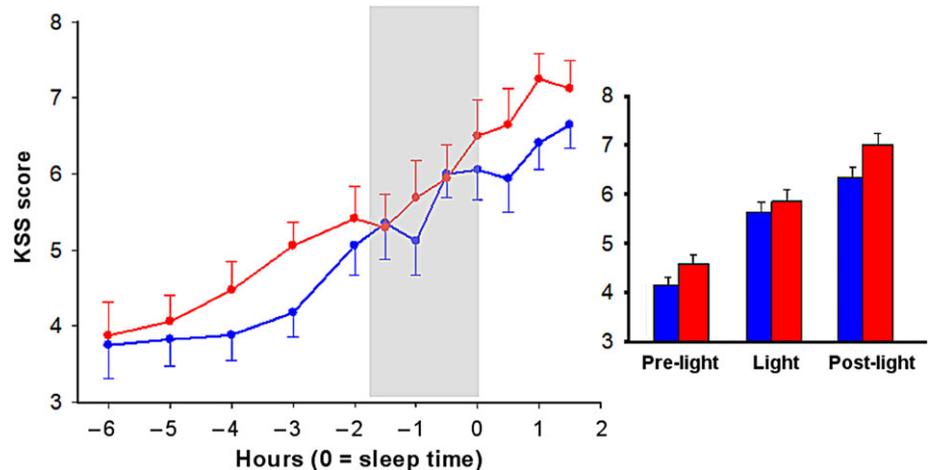
Subjective sleepiness and visual comfort

Subjective sleepiness was significantly modulated by time, $F(11, 362) = 30.52$, $p < .0001$, as well as by the light condition, $F(1, 362) = 15.14$, $p < .0005$ (Figure 4). Sleepiness increased over the protocol and subjects felt overall sleepier during the red compared to the blue light condition. The time × light condition interaction was not significant, $F(11, 362) = 0.71$, $p = .72$, however. Similarly, when averaged into three bins according to their occurrence with respect to the light exposure (pre-, during, and post-), it was observed that participants felt overall sleepier during the red light condition, but the interaction between time bin and light condition was not significant ($p > .05$). Note that volunteers already felt slightly sleepier pre-light exposure during the red compared to the blue light condition (4.1 ± 0.16 for the blue light condition, 4.6 ± 0.17 for the red light condition; but both scores fell into the range of feeling *rather alert* according to the scale). Difference in sleepiness level pre-light exposure occurred in spite of a counterbalanced within-subject design and in the context of similar sleep–wake times and subjective feelings of sleepiness as assessed by the Epworth Sleepiness Scale the week prior to lab entrance (cf. Table 1). Accounting for differences at baseline, by normalizing subjective sleepiness according to the average values of the pre-light exposure period, a significant effect of time, $F(11, 361) = 26.46$, $p < .001$, but no significant effect of light nor any time × light condition interaction was detected. Finally, subjectively perceived glare was higher for the blue compared to the red light condition (Table 3) but both light conditions had an average value between 2 (*too bright*) and 3 (*adequate*). All other measures of subjective feelings with respect to light administration, including discomfort, did not significantly differ between conditions (Table 3).

Discussion

In accordance with previous reports, our results show that polychromatic blue-enriched light administered via a head-mounted device suppresses melatonin secretion (Lovato & Lack, 2016; Paul et al., 2007; Wright et al., 2001) and improves vigilant attention, thereby eliciting classical non-visual effects of light. Concomitantly, blue-enriched light exposure did not affect cortisol or subjectively assessed discomfort when compared to a low-intensity control red light administered via the same device.

Light-induced enhancement in vigilant attention has been classically reported in in-lab settings using different light sources. Accordingly, we observed that RTs and number of

Table 3
Subjective perception of the two light conditions (means and standard deviations)

	Blue light	Red light	*p*-value
General pleasure	3.18 ± 0.88	3.18 ± 0.95	.92
Clarity	2.12 ± 0.69	2.77 ± 0.68	.05
Color	3 ± 0.79	2,82 ± 0.88	.59
Vigilance	2.35 ± 1.17	2.94 ± 1.08	.19
Concentration	2.94 ± 1.14	2.58 ± 0.79	.38
Visual comfort	4.79 ± 2.22	5.53 ± 1.95	.28

Note. Five-point Likert scales for: general pleasure, ranging from 1 (*very pleasant*) to 5 (*very unpleasant*); clarity, ranging from 1 (*much too glary*) to 5 (*much too dark*); light color, ranging from 1 (*very convenient*) to 5 (*inconvenient*); vigilance, from 1 (*helps me to stay awake*) to 5 (*makes me sleepy*); and concentration, from 1 (*helps me to stay concentrated*) to 5 (*disturbs my concentration*). Visual comfort was evaluated on a 10-point scale ranging from 1 (*highly comfortable*) to 10 (*highly uncomfortable*).

lapses of attention during the performance of a psychomotor vigilant task were reduced during and/or post- the blue-enriched condition compared to the control condition. Importantly, a previous study reported that performance on a visuomotor task was impaired using head-mounted light administration, potentially because of visual discomfort and/or sight perturbation (Paul et al., 2007). Our data suggest that when such discomfort is prevented and good sight is maintained, light exposure via head-mounted devices around bedtime can trigger the typical non-visual improvement in a measure of sustained attention using the PVT (Chellappa et al., 2011; Lockley et al., 2006). This extends previously reported improvements in cognitive flexibility when light was administered in the afternoon using the same head-mounted device (Slama et al., 2015). Light effects on performance might be potentiated when assessing performance under more challenging conditions, such as acute or partial sleep deprivation or nighttime assessments, for example (Lockley et al., 2006; Vandewalle et al., 2011). Our data reveal that vigilant attention was higher after the blue compared to the red light condition, suggesting that the impact of the light carried over on behavior, even once exposure was stopped. Note that light exposure stopped at habitual bedtime. The post-light exposure thus included a small period of wake extension (up to 1.5 hr after sleep onset), which is hallmarked not only by a higher than usual build-up of sleep pressure levels but also by the circadian gating for sleep (Lavie, 1986; Strogatz, Kronauer, & Czeisler, 1987), thus challenging the participant's levels of both sleepiness and vigilance.

Previous studies have shown that the use of smartphones or computer screens, which typically include blue-enriched LED light screens, impacted on melatonin secretion profiles when compared to smartphone and computer screens from which blue wavelengths were blocked (Cajochen et al., 2011; Heo et al., 2017; van der Lely et al., 2015). Interestingly, the differential effect of standard versus blue-light-blocked smartphones on melatonin was detected without any significant difference in cortisol levels. We did not use LED screens in the present study but, our results, like others (e.g. Chellappa et al., 2012; Santhi et al., 2012), re-emphasize that blue-enriched evening light exposure can affect the secretion of melatonin, which is a hormone regulated by the circadian system to frame the circadian night and regulate the physiological processes occurring at night. Evening head-mounted light exposure can, however, impact melatonin without affecting cortisol, an activating hormone

with a circadian secretion profile typically associated with alerting processes during daytime.

Note that the concomitant impact of blue-enriched light on both vigilance performance and melatonin expression does not imply a causal relationship between these responses. In fact, light-induced melatonin suppression is not necessarily linked to an increase in alertness (Rüger, Gordijn, Beersma, de Vries, & Daan, 2005; see also Higuchi, Fukuda, Kozaki, Takahashi, & Miura, 2011; Rahman, Marcu, Shapiro, Brown, & Casper, 2011). Also, a light-impact on vigilance performance has been detected during the daytime, hallmarked by the absence of melatonin secretion (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003; Rüger, Gordijn, Beersma, de Vries, & Daan, 2006).

The interest in light therapy is growing, as indicated, for instance, in a recent clinical trial showing its efficacy for non-seasonal major depressive disorders (Lam et al., 2016). Proper light therapy use is also developed to improve sleep quality (van Maanen et al., 2016), including in organ transplant (Burkhalter et al., 2015) and cancer (Johnson et al., 2016) patients, and to reduce social jet-lag (Geerdink et al., 2016) or prevent drowsiness at the wheel following night shift work (light is administered prior to and not during driving in the latter case; Weisgerber, Nikol, & Mistlberger, 2017). These types of applications may require light administration in conditions where one cannot remain seated in front of a light box (e.g., while keeping work duties, in flight, or in a hospital bed).

The more specific interest in head-mounted light therapy devices (also termed *light visors*) increased in the 1990s as they could lead to better compliance of the patients who could receive treatment more easily during daily activities (Stewart et al., 1990). Interestingly, head-mounted light therapy has been reported to be efficient in re-entraining circadian rhythmicity of melatonin secretion in real-life experiments consisting of six-time-zone westward travel (Boulos et al., 2002). Likewise head-mounted light therapy was reported to improve well-being at work in hospital medical staff (Bragard & Coucke, 2013). Furthermore, head-mounted devices were first considered efficient as they led to similar reduction in depressive symptoms when compared to standard light boxes (Stewart et al., 1990). They were also shown to be an efficient replacement for light boxes when normal light-box treatment had to be temporally interrupted (i.e., after treatment initiation) when a patient was unable to use a light box (e.g., travel; Clark et al., 1997). Other studies, however, failed to find positive

results when compared to a placebo/control condition (Levitt et al., 1996; Rosenthal et al., 1993; Teicher et al., 1995). Reasons for such discrepancies are unclear and may reside in the light used as the control condition (e.g., 400-lx white light [Rosenthal et al., 1993], which may be too high for a control condition when considering more recent findings on the non-visual impact of light [Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000]) or as active treatment (e.g., 600-lx white light [Teicher et al., 1995], which is lower than standard white light therapy [Pail et al., 2011]). The present study does not resolve such debate. However, given that the administered blue-enriched light was successful in triggering non-visual responses, our results encourage further assessments, especially circadian phase shifting properties. It has to be mentioned that our protocol did not include a control condition without any light administration. We opted for a red light control condition to minimize expectation effects and because longer wavelength light is generally considered to induce little non-visual effect of light on physiology and behavior (Brainard et al., 2001; Chellappa et al., 2011; Gaggioni et al., 2014; Lockley et al., 2006; Thapan, Arendt, & Skene, 2001). Red light has, however, been suggested in some studies to affect melatonin circadian rhythmicity, cortisol secretion, and alertness (Figueiro, Bierman, Plitnick, & Rea, 2009; Figueiro & Rea, 2010; Ho Mien et al., 2014). Future studies should consider using other control conditions (e.g., dim light or normal ambient indoor light) to further assess the impact of blue-enriched light administration through head-mounted devices. Whether differences in light color also contribute to the effect we report should also be investigated.

As they deliver light from a very short distance, head-mounted devices have been reported to generate discomfort (Paul et al., 2007, 2015). In addition, exposure to light has been reported to trigger glucocorticoid release through melanopsin photoreception signals (Pilorz et al., 2016). Using a head-mounted device preserving good sight during exposure, our results suggest that the blue-enriched light does not elicit different levels of discomfort compared to the red-light control condition, whether measured by subjective scales or physiological stress assessed via salivary cortisol. In addition, no volunteers reported headache, eyestrain, nausea, or agitation, the most common light therapy side-effects, during or after light administration (Pail et al., 2011). This low incidence of apparent adverse effects/discomfort might be due to the use of lower-intensity blue-enriched light (1500 lx) than previous head-mounted devices (8000 lx; Paul et al., 2007). As indicated by the standard errors of our subjective measures, there is, however, some inter-individual variability in light perception. Some participants reported blue-enriched light as having too much glare ($n = 10$; < 2 on the Likert scale) or being uncomfortable ($n = 8$; < 5 on the Likert scale). Note that in the present study, light was administered while ambient light was dim (5 lx). This type of condition can increase backlight effects and trigger some discomfort. It is therefore likely that under normal use (i.e., under higher ambient light in the home environment), any potential discomfort may be lower. Nevertheless, the long-term use (e.g., exposure over a longer period) of these devices on sight, visual comfort, and also stress and non-visual responses should be further investigated. Also, the repetitive use of such light sources will putatively trigger their phase-resetting properties on the circadian clock, which might not be recommended in individuals who are well entrained to the light–dark cycle. Besides exposure duration and frequency, time of exposure should also be considered as determinant for the effects of light on physiology and behavior. Here we probed the impact of a single exposure of light administered in the evening hours. We chose this time window because the latter coincides with the onset of melatonin secretion, one of our main variables of interest. It has to be mentioned, however, that both phase-resetting and acute effects of light on physiology and behavior depend on circadian phase. According to the phase-response curve of light (Jewett et al., 1997), morning exposure induces a phase advance, while evening exposure leads to phase delays. In the same vein, the acute effects of light depend on time of day (Vandewalle et al., 2011). Thus, these data cannot be generalized to light administration over the 24-hr cycle.

To sum up, our results suggest that a new-generation head-mounted light device may be efficient to improve alertness in conditions triggering high levels of sleepiness (e.g., long work hours, insufficient sleep) or in patient populations suffering from high levels of sleepiness. Since head-mounted light administration was able to suppress melatonin, which is central to circadian rhythmicity, the head-mounted light device might also be efficient to phase shift circadian rhythms. If one uses the head-mounted light device solely to acutely improve alertness, this phase-shifting effect should be considered as it may not be desired. In contrast, the potential light-induced phase

shifting may be important for jet-lag, shift work, or mood disorders, as suggested with other recent head-mounted devices (Lovato & Lack, 2016; Wright et al., 2001). This potential phase-shifting impact must be further investigated, however. Future in-lab and field studies should investigate the impact of head-mounted light delivery at different times of day and under different sleep pressure levels (e.g., during nighttime, under jet-lag) and reevaluate whether it improves vigilance and/or shifts circadian phase. Finally, the device's efficiency for treating health conditions, such as mood disorders, should be further investigated.

Disclosure of conflict of interest

Acknowledgments

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