Short-wavelength attenuated polychromatic white light during work at night: limited melatonin suppression without substantial decline of alertness

Maan van de Werken, Marina C. Giménez, Bonnie de Vries, Domien G. M. Beersma, and Marijke C. M. Gordijn

Department of Chronobiology, Centre for Life Sciences, University of Groningen, Groningen, The Netherlands

Exposure to light at night increases alertness, but light at night (especially short-wavelength light) also disrupts nocturnal physiology. Such disruption is thought to underlie medical problems for which shiftworkers have increased risk. In 33 male subjects we investigated whether short-wavelength attenuated polychromatic white light (λ<530 nm filtered out) at night preserves dim light melatonin levels and whether it induces similar skin temperature, alertness, and performance levels as under full-spectrum light. All 33 subjects participated in random order during three nights (at least 1 wk apart) either under dim light (3 lux), short-wavelength attenuated polychromatic white light (193 lux), or full-spectrum light (256 lux). Hourly saliva samples for melatonin analysis were collected along with continuous measurements of skin temperature. Subjective sleepiness and activation were assessed via repeated questionnaires and performance was assessed by the accuracy and speed of an addition task. Our results show that short-wavelength attenuated polychromatic white light only marginally (6%) suppressed salivary melatonin. Average distal-to-proximal skin temperature gradient (DPG) and its pattern over time remained similar under short-wavelength attenuated polychromatic white light compared with dim light. Subjects performed equally well on an addition task under short-wavelength attenuated polychromatic white light compared with full-spectrum light. Although subjective ratings of activation were lower under short-wavelength attenuated polychromatic white light compared with full-spectrum light, subjective sleepiness was not increased. Short-wavelength attenuated polychromatic white light at night has some advantages over bright light. It hardly suppresses melatonin concentrations, whereas performance is similar to the bright light condition. Yet, alertness is slightly reduced as compared with bright light, and DPG shows similarity to the dim light condition, which is a physiological sign of reduced alertness. Short-wavelength attenuated polychromatic white light might therefore not be advisable in work settings that require high levels of alertness.

Keywords: Health, humans, light at night, performance, skin temperature, sleepiness

INTRODUCTION

In industrialized countries, about 15–30% of the working population is involved in some kind of permanent night and rotating shiftwork (Boivin et al., 2007; Haus & Smolensky, 2006). This means that many people are exposed to light and to darkness at atypical biological times because their work and subsequent sleep are not synchronized with the natural light-dark cycle. Sleeping and working out of phase with the body’s circadian rhythms for longer periods can cause (chronic) fatigue and affect performance and cognitive functions (Costa, 1996; Härmä et al., 2002; Wright et al., 2006). Moreover shiftwork has been associated with health problems including cardiovascular disease, impaired glucose and lipid metabolism, type 2 diabetes, gastrointestinal discomfort such as stomachache or diarrhea, reproductive difficulties, and cancer (Haus & Smolensky, 2006; Jasser et al., 2006; Mahoney, 2010; Morikawa et al., 2005; Rüger & Scheer, 2009; Straif et al., 2007; Viswanathan & Schernhammer, 2009).

The medical problems encountered by shiftworkers are thought to result from disturbed physiological rhythms, circadian misalignment, and sleep debt (Rajaratnam & Arendt, 2001; Rüger & Scheer, 2009; Scheer et al., 2009; Van Cauter et al., 1997). Being exposed to light at night shifts the phase of the central master clock in the brain (suprachiasmatic nucleus [SCN]), which is responsible for synchronizing endogenous circadian rhythms, such as the melatonin rhythm, and the rhythm of peripheral clocks. Light, and especially short-wavelength light, the blue part of the light...
spectrum, entrains circadian rhythms in humans (Lockley et al., 2003; Revell & Eastman, 2005; Rüger et al., 2012; Warman et al., 2003), but also exerts an acute suppressing effect upon melatonin production (Brainard et al., 2001; Thapan et al., 2001). In addition, short-wavelength light suppresses sleepiness (Cajochen et al., 2005) and increases alertness (Revell et al., 2006) effectively, which is beneficial for performance at night (Chellappa et al., 2011). These specific effects of short-wavelength light are attributed to nonvisual photoreceptive input by specific retinal ganglion cells towards the SCN (Gooley et al., 2003; Hattar et al., 2002). These cells express a specific photopigment, melanopsin, which has a peak absorbance around 480 nm, with an approximate upper boundary at 540 nm (Dacey et al., 2005; Walker et al., 2008).

Long-term suppression of melatonin production is thought to play an important role in increased prevalence of cancer in shiftworkers (Flynn-Evans et al., 2009; Schernhammer & Schulmeister, 2004; Straif et al., 2007; Viswanathan & Schernhammer, 2009). Direct protective roles of melatonin against cancer development have been proposed: antiproliferative effects (Blask, 1984; Blask et al., 1999), antioxidant effects (Blask et al., 2002; Brzezinski, 1997), immunostimulatory effects (Brzezinski, 1997; Panzer & Viljoen, 1997), and modulation of the expression of the tumor suppressor gene p53 (Mediavilla et al., 1999). Shiftwork has also been associated with increased prevalence of diabetes and the metabolic syndrome (Karlsson et al., 2001; Morikawa et al., 2005). This is thought to be caused by disrupted physiological rhythms in peripheral tissues (Staels, 2006). Melatonin may play a crucial role here as well, for melatonin has been shown to shift insulin secretion rhythms of isolated pancreatic tissue of rats (Peschke & Peschke, 1998).

In our 24-h society, it becomes more and more important to unravel the biological mechanisms that are involved in the development of health problems in shiftworkers and to investigate different countermeasures. One of such measures, the use of short-wavelength attenuated polychromatic white light, was investigated in the present study. From an economic point of view, it seems beneficial to expose shiftworkers to full-spectrum light at night to increase alertness and improve performance at night. On the other hand, if working under full-spectrum light at night is detrimental for health on the long term, alternatives such as short-wavelength attenuated polychromatic white light should be subject of investigation. To assess the magnitude of possible decrements in performance under short-wavelength attenuated polychromatic white light, we included an addition task and measures of subjective sleepiness, subjective activation, and skin temperature during prolonged wakefulness while working at night. Skin temperature is linked to sleepiness (Kräuchi et al., 1997, 2004) and vigilance (Raymann & Van Someren, 2007). Sleep initiation is preceded by a rise in distal skin temperature (Kräuchi et al., 1999, 2000) and experimentally warming extremities reduces the time needed to fall asleep in healthy subjects (Raymann et al., 2005, 2007). During night sleep, distal skin temperatures remain high and core body temperature drops (Kräuchi et al., 2000) and this process has a strong circadian component (Gradisar & Lack, 2004). Upon waking up, skin temperature declines and during this stage lower skin temperatures are linked to decreased sleepiness and increased activation (Kräuchi et al., 2004; Van de Werken et al., 2010). Indeed, cooling instead of warming of the skin increased vigilance in narcolepsy patients (Frönzcek et al., 2008). The physiological functions of skin temperature dynamics during day and night, other than those associated with sleep, are not well known compared with our understanding of the actions of melatonin. However, a disturbance in the regular dynamics of thermal regulation may also have negative effects on health, unknown to us thus far.

In the present study, we studied 33 male subjects in three conditions in three separate nights (at least 1 wk apart in randomized order): a dim light condition, a short-wavelength attenuated polychromatic white light condition, and a full-spectrum light condition. We investigated the effects of these light conditions on subjective ratings of sleepiness and activation, performance on an addition task, melatonin levels, and the distal-to-proximal skin temperature gradient (DPG) (Kräuchi et al., 2000; Rubinstein & Sessler, 1990).

MATERIALS AND METHODS

Subject Characteristics

Subjects (33 healthy males, mean age [±SD] 22.6 ± 2.2 yrs) did not have sleep disorders (Pittsburgh Sleep Quality Index < 6; Buysse et al., 1989), somatic diseases, depressed mood (Beck Depression Inventory-II < 8; Beck et al., 1996, 2002), chronic diseases color blindness (Ishihara test; Clark, 1924), or visual impairment (assessed by general health questionnaire). Subjects did not use medication (assessed by general health questionnaire). Neither did they work in night shifts or traveled across more than one time zone respectively 3 and 1 mo preceding the study. Subjects had an average chronotype for their gender and age (mean midsleep on free days [±SD] 5:45 h ± 43 min, with a mean sleep onset [±SD] at 01:24 h ± 58 min and a mean sleep offset [±SD] at 10:05 h ± 49 min, rated on the Munich Chronotype Questionnaire; Roenneberg et al., 2003). Subjects did not report excessive intake of caffeinated drinks (average cups a day [±SD] 2 ± 2) or alcohol (average glasses a week [±SD] 8 ± 5), were nonsmoking, and did not use drugs (assessed by general health questionnaire). The study protocol was approved by the Medical Ethics Committee of the University Medical Center of Groningen, The Netherlands, and conformed to international ethical standards (Portaluppi et al., 2008). All subjects gave
written informed consent and were financially compensated for their participation.

**Experimental Design**

In this paper, the results of two similar studies were combined. These studies differed in a single aspect: in Study I subjects stayed together with other participants in one room and in Study II all subjects stayed in individual rooms. The studies consisted of three nights from 21:00 till 7:00 h in the laboratory, with a minimum of 1 wk between successive measurements (see Figure 1). The first study in which 17 subjects participated was carried out between October 10 and November 22, 2008, and the second study in which 16 subjects participated was carried out between June 19 and August 7, 2010. Only in Study I the experiment continued the subsequent day at home until 23:00 h, during which urine was collected for 6-sulfatoxymelatonin (aMT6s) analysis. During the first 2 h of each night, subjects stayed in dim light (<5 lux). In the first hour (21:00–22:00 h), subjects were oriented to study the protocol (data not included, except for salivary melatonin concentration). During the second hour (22:00–23:00 h), baseline data were collected. In random order, from 23:00 till 7:00 h subjects stayed in one of the following three conditions: (1) dim light (horizontal light intensity [±SD] 1 ± 1 lux, vertical light intensity at the level of the eye [±SD] 3 ± 2 lux); (2) short-wavelength attenuated polychromatic white light (horizontal light intensity [±SD] 438 ± 101 lux, vertical light intensity at the level of the eye [±SD] 193 ± 108 lux; short-wavelength [<530 nm] reducing foil [heat shrinkable tubing; WLF-NR400-4-SP; Tyco Electronics, UK] melted around a Philips TL-D 36W/830, aimed to reduce nonvisual photoreception via melanopsin, total irradiance from 420 to 530 nm = 0.0 W/m²); or (3) full-spectrum light (horizontal light intensity [±SD] 625 ± 151 lux, vertical light intensity at the level of the eye [±SD] 256 ± 131 lux, total irradiance from 420 to 530 nm = 0.14 W/m²; Philips TL-D 36W/830); see Figure 2 for the spectral

![FIGURE 1](image1.png) Overview of the experimental design; for the experimental details refer to the Experimental Design section (Materials and Methods).

![FIGURE 2](image2.png) Spectral power distribution. Short-wavelength attenuated polychromatic white light (thick line) was obtained by melting a yellow filter (see Materials and Methods for specifications) on top of a 830 TL tube (3000 K), which was also used in the full-spectrum light condition (thin line).
composition of the lights. Subjects were placed in the same location in the room in all three conditions to reduce within individual variation in light intensities and stayed seated behind their computers as far as possible. Subjects were not allowed to sleep at any time during the experiment. Hourly snacks of 100 calories and 130 mL water (room temperature) were supplied. Computer screens and dim lights were covered with a color filter (E-colour +, 105 Orange; Rosco Laboratories, London, UK) to decrease short-wavelength light transmission.

Measurements

Salivary Melatonin

Each hour (from 21:30 till 6:30 h), saliva samples were collected using cotton swabs (Salivettes; Sarstedt, Etten-Leur, The Netherlands). Melatonin concentration was assessed by radioimmunoassay (RK-DSM; Bühlmann Laboratories, Alere Health, Tilburg, The Netherlands). Each sample was analyzed once and all samples from each individual were analyzed together within the same assay. Analytical sensitivity: 0.2 pg/mL; intra- and interassay coefficients of variability: 7.8% (mean 14.5 pg/mL) and 13.8% (mean 17.6 pg/mL), respectively.

Two baseline measurements were carried out in each condition in dim light (at 21:30 and 22:30 h).

Urinary 6-Sulfatoxymelatonin (aMT6s)

Just before the experimental light condition was set in the first study (at 23:00 h), subjects were asked to empty their bladder. From here on, total 24-h urine production was collected at three 8-h intervals. Urine from the second (7:00–15:00 h) and third (15:00–23:00 h) intervals was collected at home. aMT6s concentration was assessed by enzyme-linked immunosorbent assay (ELISA; EK-M6S; Bühlmann Laboratories, Alere Health). Each sample from one individual was analyzed within the same assay. Analytical sensitivity: 0.14 ng/mL; intra- and interassay coefficients of variability: 10.6% (mean 25.3 ng/mL) and 21.2% (mean 26.1 ng/mL), respectively. Total aMT6s excretion was calculated by multiplying concentration and volume.

Distal-to-Proximal Skin Temperature Gradient

Skin temperatures were recorded throughout the night at a rate of one sample per minute. Recording ended immediately after the last testing periods at 7:00 h. Skin temperature was measured using Ibuttons (DS1922L; Maxim Integrated Products, Sunnyvale, CA, USA; resolution 0.0625 °C; for further technical details and validation of the use of Ibuttons to measure skin temperature, see Van Marken Lichtenbelt et al., 2006) that were placed on the base of left and right middle fingers (distal skin temperature) and left and right infraclavicular regions (proximal skin temperature). The DPG was calculated as distal minus proximal skin temperature.

Subjective Ratings of Sleepiness and Activation

Subjective ratings of sleepiness (Karolinska Sleepiness Scale; Åkerstedt & Gillberg, 1990) and activation (two factors of the Thayer adjective checklist; Thayer, 1967) were determined hourly.

Addition Task

Every hour, subjects made as many correct additions as possible within a 3-min interval using a custom-made computer test. All additions consisted of two random numbers of two digits each.

Statistical Analysis

The differences over time of salivary melatonin, urinary aMT6s, subjective ratings of sleepiness, activation, and the addition task were tested with a repeated-measures analysis of variance (ANOVA) with one within factor (time) and one within factor (condition). The percentage of melatonin suppression is calculated by comparing the area under the curve in the dim light condition with the area under the curve in the short-wavelength attenuated polychromatic white light and full-spectrum light condition over the whole night (from 23:30 till 6:30 h). Percentage of correct additions was tested nonparametrically (k related samples) with a Friedman test. Baseline measurements were tested separately, to check whether already at this moment a difference could be observed between the three conditions. Study was included as a between-subject factor and was maintained in the model if it contributed significantly (either as main effect or in interaction with condition or with condition × time), which was only the case for salivary melatonin and subjective activation. We detected that in Study I absolute salivary melatonin levels were slightly lower than in Study II across the three conditions (p = 0.02). Within the analysis on subjective ratings of activation, we detected an interaction between study and condition (p = 0.03). These results, also taking into account that in exploring the effects of study we carried out multiple tests for which we did not correct p values upwards, indicate that there are no strong differences between these two data sets that confound our interpretations.

Skin temperature outliers (defined as quartile + (2 × interquartile range)) were deleted and interpolated. This resulted in data loss at the end of the night because data could not be interpolated there, resulting in a maximum of 12-min data reduction to which all subjects were truncated. For the analysis of the resulting DPG, we used mixed-effect regression analysis using MLwiN software (Centre for Multilevel Modelling, Institute of Education, London, UK). The analyses take the hierarchical structure of the design into account, in our case the temperature measurements i that were nested within participants j, once more nested within condition k, and
A Pearson correlation was used to show the relationship between the change in melatonin and the change in DPG with the change in sleepiness and activation between the dim light and short-wavelength attenuated polychromatic white light conditions and between the dim light and the full-spectrum light conditions. These values were first z-transformed as follows: the difference of each individual measurement between conditions (from 23:00 to 6:30 h) was first averaged per subject and then averaged for all subjects, the overall average was subtracted from the average per subject and then divided by the SD of the overall average for all subjects.

For graphical purposes only, salivary melatonin was normalized to the maximum value of the best-fitted melatonin curve (Van Someren & Nagtegaal, 2007) in the dim light condition, and the number of correct additions were normalized as follows: all samples per subject were divided by the average of all samples over the dim light condition per subject (indicated by the dotted line in the graph) (from 23:00 to 6:00 h) and then multiplied by 100%.

Values are described as average ± SEM. All tests were two tailed with a 0.05 level of significance.

RESULTS

Salivary Melatonin
At baseline (21:30 and 22:30 h), before initiating the three light conditions, salivary melatonin values were similar \( (F_{2,30} = 0.95, \text{nonsignificant [NS]} \) between conditions. In the dim light and short-wavelength attenuated polychromatic white light conditions, melatonin remained high throughout the night, whereas within the full-spectrum light condition, melatonin was suppressed compared with dim light and short-wavelength attenuated polychromatic white light (Figure 3; dim light).
light: $F_{1,31} = 32.69$, $p < 0.001$, short-wavelength attenuated polychromatic white light: $F_{1,31} = 27.62$, $p < 0.001$; interaction with time, dim light: $F_{7,25} = 12.15$, $p < 0.001$, short-wavelength attenuated polychromatic white light: $F_{7,25} = 3.13$, $p < 0.05$). Within the short-wavelength attenuated polychromatic white light condition, melatonin was significantly suppressed relative to dim light ($F_{1,31} = 5.27$, $p < 0.05$; interaction with time, $F_{7,25} = 1.51$, NS), but suppression was small (6 ± 4%) compared with the suppression in the full-spectrum light condition (45 ± 6%).

**Urinary 6-Sulfatoxymelatonin (aMT6s)**

Melatonin production as measured by aMT6s excretion showed significantly different patterns between conditions over the 24-h period (Figure 4; $F_{4,13} = 10.12$, $p = 0.001$). Post hoc tests revealed that the difference in pattern over time was caused by a significantly lower aMT6s concentration in the full-spectrum light condition compared with both the dim light and short-wavelength attenuated polychromatic white light conditions in the interval 23:00–7:00 h (dim light: $F_{1,16} = 19.47$, $p < 0.001$; short-wavelength attenuated polychromatic white light: $F_{1,16} = 39.05$, $p < 0.001$). At the same interval, a trend was observed suggesting lowered melatonin in the short-wavelength attenuated polychromatic white light compared with the dim light condition ($F_{1,16} = 4.17$, $p = 0.06$), which fits the salivary melatonin data. That the differences in aMT6s concentrations are found only at this first interval and not in the second interval, which reflects early morning melatonin levels, suggests that the largest differences in melatonin levels between light conditions are found in the middle of the night. This pattern fits with the salivary melatonin data as well.

**Distal-to-Proximal Skin Temperature Gradient**

With respect to DPG, the three conditions did not differ at the start of the experiment ($p$ values ≥ 0.5). DPG rose in the dim light and short-wavelength attenuated polychromatic white light conditions (Figure 5), with a similar trajectory over the whole night ($β$ estimate ± error: Condition × Linear time = 0.03 ± 0.17 °C h$^{-1}$; Condition × Sqrr(time) = −0.12 ± 4.19 °C h$^{-1}$). The rise in DPG was not observed in the full-spectrum light condition. This resulted in significantly different trajectories of DPG in the full-spectrum light condition compared with the dim light and short-wavelength attenuated polychromatic white light conditions (vs. dim light: Condition × Linear_time = 0.51 ± 0.17 °C h$^{-1}$, $p < 0.005$; Condition × Sqrt(time) = −1.17 ± 4.26 °C h$^{-1}$, $p < 0.01$; vs. short-wavelength attenuated polychromatic white light: Condition × Linear_time = 0.48 ± 0.18 °C h$^{-1}$, $p < 0.01$; Condition × Sqrt(time) = −1.62 ± 4.59 °C h$^{-1}$, $p < 0.05$) and a significantly lower average DPG in the experimental night under full-spectrum light (dim light: $F_{1,32} = 15.39$, $p < 0.001$; short-wavelength attenuated polychromatic white light: $F_{1,32} = 5.30$, $p < 0.05$) compared with dim light and short-wavelength attenuated polychromatic white light (which were not significantly different, $F_{1,32} = 2.27$, NS).

**Subjective Sleepiness and Activation**

At baseline (22:00 h), subjective sleepiness did not differ significantly between conditions ($F_{2,31} = 0.82$, NS) nor did subjective activation ($F_{2,30} = 0.42$, NS). Sleepiness increased significantly during the course of the night (Figure 6a; $F_{7,26} = 18.07$, $p < 0.001$), but no significant differences were found between the three conditions (condition: $F_{2,31} = 2.77$, NS). Sleepiness showed a significantly different pattern over time between the three conditions (condition × time: $F_{1,19} = 2.73$, $p < 0.05$; this was not solely attributable to the small spike at 3:00 h in the dim light condition; without these data in the analysis the interaction remained significant). Activation decreased significantly during the night (Figure 6b; $F_{7,25} = 35.94$, $p < 0.001$), with a similar pattern over time between the three conditions ($F_{4,18} = 1.95$, NS). No significant difference was found between the dim light and short-wavelength attenuated polychromatic white light conditions ($F_{1,31} = 1.43$, NS). However, both conditions differed significantly from the full-spectrum light condition (dim light: $F_{1,31} = 5.54$, $p < 0.05$; short-
wavelength attenuated polychromatic white light: $F_{1,31} = 6.33$, $p<0.05$).

Addition Task
During the baseline measurement (22:00 h), no significant differences between conditions were found in the number of correct additions obtained during a 3-min interval by the subjects (dim light: 36 ± 2, short-wavelength attenuated polychromatic white light: 37 ± 2, full-spectrum light: 38 ± 2; $F_{2,31} = 0.62$, NS) nor in the percentages of additions that were correct (dim light: 95%, short-wavelength attenuated polychromatic white light: 95%, full-spectrum light: 96%; $\chi^2 = 1.27$, NS).

During the experimental periods, subjects performed equally well in each lighting condition in terms of the fraction of correctly made additions (average percentage correct additions, dim light: 96%, short-wavelength attenuated polychromatic white light: 96%, full-spectrum light: 96%; $\chi^2 = 1.70$, NS). The total number of correct additions made (Figure 7) was higher in the short-wavelength attenuated polychromatic white light (on average 40 ± 2; $F_{1,32} = 18.30$, $p<0.001$) and in the full-spectrum light (on average 40 ± 2; $F_{1,32} = 15.87$, $p<0.001$) conditions compared with the dim light condition (on average 36 ± 2), whereas no significant difference was found between the short-wavelength attenuated polychromatic white light and full-spectrum light conditions ($F_{1,32} = 0.01$, NS). This suggests that subjects perform better under full-spectrum light and short-wavelength attenuated polychromatic white light conditions because they work faster at a similar error rate compared with the dim light condition. Conditions differed in their pattern over time ($F_{14,19} = 2.34$, $p<0.05$), during which the number of correct additions on average decreased (time: $F_{7,26} = 6.92$, $p<0.001$).

Relationships Between Melatonin, DPG, Sleepiness, and Activation
The difference in melatonin between the dim light condition and the short-wavelength attenuated polychromatic white light condition or full-spectrum light condition did not correlate with the difference in sleepiness or activation between these conditions (dim light vs. short-wavelength attenuated polychromatic white light: sleepiness $r = 0.094$, NS, activation $r = 0.182$, NS; full-spectrum light: sleepiness: $r = 0.094$, NS, activation: $r = 0.185$, NS). However, between the dim light and full-spectrum light conditions, the correlations between the difference in subjective ratings and difference in DPG were significant (sleepiness: $r = 0.437$, $p<0.05$; activation: $r = 0.401$, $p<0.05$), indicating that with increasing DPG people felt more sleepy and less subjectively activated. The degree of melatonin suppression under short-wavelength attenuated polychromatic white light or full-spectrum light did not correlate to the difference of DPG under dim light with short-wavelength attenuated polychromatic white light or full-spectrum light (short-wavelength attenuated polychromatic white light: $r = -0.182$, NS; full-spectrum light: $r = 0.105$, NS).
FIGURE 6. Subjective sleepiness and activation. (a) Mean (±SEM) subjective ratings of sleepiness (Karolinska Sleepiness Scale, 1 = lowest and 9 = highest sleepiness) and (b) mean (±SEM) subjective ratings of activation (Thayer adjective checklist, 10 = lowest and 40 = highest activation) in the dim light (black squares), short-wavelength attenuated polychromatic white light (gray circles), and full-spectrum light (white circles) light conditions (n = 33). Baseline measurements were performed at 22:00 h in dim light.

Scatterplots of the correlations described above are available as Supplementary Material.

DISCUSSION

This study shows that when healthy male individuals are exposed to short-wavelength attenuated polychromatic white light at night, both salivary melatonin profile and average salivary melatonin concentration are only marginally, but significantly, affected (on average 6 ± 4% suppression) compared with the same situation in dim light. As expected, a clear suppression of melatonin was observed under full-spectrum light (on average 45 ± 6% compared with dim light). Similar results were found for urinary aMT6s concentration measured in a subsample of our subjects. Two earlier studies (Kayumov et al., 2005; Rahman et al., 2011) also found some melatonin suppression when short-wavelengths were filtered out, but not significantly so. This is surprising because both these studies used short-wavelength attenuated light conditions that can be predicted to result in higher melatonin suppression compared with our study; in the study of Rahman et al. less of the spectrum was filtered out (filters used at the level of the eye: 0% transmission <480 nm) and higher light intensities were used (439 lux in angle of gaze) than in our study (193 lux at the level of the eye) and Kayumov et al. also used higher light intensities (800 lux), but with a similar filtering of the
spectrum (<530 nm, using goggles with filters). With a larger sample size than both these studies (33 subjects in the current study vs. 12 and 19 subjects in Rahman et al. and Kayumov et al., respectively), we now detect a significant but only small suppression of melatonin (6%) under short-wavelength attenuated polychromatic white light. This effect could be due to some activation at the edge (around 550 nm; see Figure 2) of the action spectrum of melatonin suppression (Brainard et al., 2001; Thapan et al., 2001) by the short-wavelength attenuated polychromatic white light. This could mean that melanopsin expressing retinal ganglion cells are responsible for the suppression of melatonin we observe and/or that the visual system of rods and cones is contributing. Connections of rods and cones with the intrinsically photosensitive retinal ganglion cells (ipRGCs) are presumed to be responsible for rod/cone input towards the SCN (Belenky et al., 2003; Hatori & Panda, 2010; Wong et al., 2007). Indeed at relatively low intensities, “green” light (555 nm) can suppress melatonin as effectively as “blue” light (460 nm), but this effect is progressively lost with increasing duration of light exposure (measured up to 6.5 h) (Gooley et al., 2010). This fits with the melatonin suppression by short-wavelength attenuated polychromatic white light that we observed during the first 4–5 h, but not at the end of the protocol (Figure 3). That the suppression of melatonin in our short-wavelength attenuated polychromatic white light condition did not reach the degree of melatonin suppression in the full-spectrum light condition as for “green” light in Gooley et al. (2010) suggests that light across only a range of wavelengths can elicit this combined response. In support of this, high-intensity “red” light (630 nm) was not able to induce melatonin suppression in humans (Hanifin et al., 2006). Physiologically, this could mean that both cones and ipRGCs have to be excited to obtain signal transduction towards the SCN, limiting these responses to the wavelengths at which both these photoreceptors are excited, namely the “blue” towards “green” light. The “green” proportion in the spectrum of the short-wavelength attenuated polychromatic white light condition we used (Figure 2) was probably not sufficient to elicit this response fully. Possibly illustrative of how small differences in the amount of “blue” light filtered can effect study outcomes, a study that used orange lenses glasses, which filtered out more wavelengths (<540 nm) than our study, reported no melatonin suppression compared with a gray lenses glasses condition (14 subjects; Sasseville et al., 2006). On average, even a slight nonsignificant increase was found. In this study, even higher light intensities (1300 lux at the eye level) were used than the two other studies on melatonin suppression under short-wavelength attenuated light (Kayumov et al., 2005; Rahman et al., 2011), including our study. The two separate studies that were combined in this paper were performed in groups or in isolation, and also in different seasons, namely winter and summer. That we find across these two studies consistent effects of short-wavelength attenuated polychromatic white light strengthens the potential general applicability of short-wavelength attenuated polychromatic white light. The degree of melatonin suppression in response to full-spectrum light has been shown to

FIGURE 7. Number of correct additions. Mean (±SEM) number of correct additions in the dim light (black square), short-wavelength attenuated polychromatic white light (gray circles), and full-spectrum (white circles) light conditions (n = 33). The number of correct additions made during a 3-min time interval were normalized within subjects relative to their dim light average from 23:00 up to 6:00 h inclusive (indicated by the dotted line). Baseline measurements were done at 22:00 h in dim light.
depend upon prior light history (Hébert et al., 2002; Higuchi et al., 2007; Smith et al., 2004). However, in comparing the two studies (i.e., seasons) included here we do not detect significantly different levels of melatonin suppression (no interaction effect of condition × study or condition × time × study; see also the Statistical Analysis section).

Subjective sleepiness showed the characteristic increase during the night, which is the result of increased homeostatic sleep pressure due to prolonged wakefulness in combination with a high circadian pressure for sleep at the end of the night (Dijk & Edgar, 1999). Subjects, however, did not feel significantly sleepier under dim light or short-wavelength attenuated polychromatic white light compared with full-spectrum light. The average full-spectrum light intensities (256 lux) that we used are around the inflection point of the S-shaped dose-response curve of light intensity against sleepiness (Cajochen et al., 2000). Indoors, these light intensities are often used and are therefore relevant to a potential shiftwork application. Effects of light of these intensities may not show consistent results across all parameters considered, because different physiological responses can have differently shaped dose-responses to light. This may be why we do detect an effect on melatonin suppression, but no effect on sleepiness. This already suggests, and correlational analysis confirmed this, that under the light intensities used, there is no association between sleepiness and (physiological) melatonin concentrations at night. This is contrary to earlier results from Cajochen et al. (1996, 2000) but in line with the conclusion of Rüger et al. (2005). Interestingly, higher DPG was significantly associated with both increased sleepiness and lowered activation, in concordance with earlier experimental work (melatonin administration) carried out during the day (Kräuchi et al., 2006).

Short-wavelength attenuated polychromatic white light negatively affected activation contrary to earlier reports (Kayumov et al., 2005; Rahman et al., 2011). Also skin temperature, a physiological parameter linked to sleepiness and vigilance, was similar in the short-wavelength attenuated polychromatic white light condition and the dim light condition. These two results do suggest a possible decrement in overall performance, vigilance, and efficiency, although performance on an addition task was not negatively affected by short-wavelength attenuated polychromatic white light. If exposure to full-spectrum light at night is indeed involved in the causation of the detrimental effects of shiftwork on health, short-wavelength attenuated polychromatic white light at night has the potential to improve health in shiftwork. Note that in our study we only included relatively young healthy males and that direct extrapolation towards a more variable shiftwork workforce with a wider range of ages and including females will require further study. Our results also indicate that short-wavelength attenuated polychromatic white light may not be applicable in all settings. Especially when safety of others or of the shiftworker is at stake, implementation of a severe reduction of short-wavelength light might not be advisable.

ACKNOWLEDGMENTS

We thank the subject volunteers for their participation, Luc Schlangen and Peter van der Burgt (Philips Lighting) for providing the lamps and short-wavelength reducing foil used in this study, and Lotte van Nierop, WolterStam, Vincent Hulst and JoopLuider for practical assistance.

DECLARATION OF INTEREST

Financial support was obtained from the 6th European Framework project EUCLOCK (018741).

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

REFERENCES


Notice of Correciton:
A Change has been made to the abstract of this article since its original online publication date of May 24, 2013.

Supplementary material can be found in the online edition of this article.