Effect of daylight LED on visual comfort, melatonin, mood, waking performance and sleep

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LED light sources have a discontinuous light spectrum with a prominent 'blue' peak between 450 and 470 nm that influences non-image forming responses in humans. We tested an LED lighting solution mimicking a daylight spectrum on visual comfort, circadian physiology, daytime alertness, mood, cognitive performance and sleep. Fifteen young males twice spent 49 hours in the laboratory under a conventional-LED and under a daylight-LED condition in a balanced cross over design flanked by a baseline and a post-light exposure night. Despite different light spectra, the photopic lux and the correlated colour temperature of the lighting were the same for both LEDs. The colour rendering index and the melanopic strength were 25.3% and 21%, respectively, higher for the daylight LED than the conventional LED. The volunteers had better visual comfort, felt more alert and happier in the morning and evening under daylight LED than conventional LED, while the diurnal melatonin profile, psychomotor vigilance and working memory performance were not significantly different. Delta EEG activity (0.75–4.5 Hz) was significantly higher after daylight-LED than conventional-LED exposure during the post-light exposure night. We have evidence that a daylight-LED solution has beneficial effects on visual comfort, daytime alertness, mood and sleep intensity in healthy volunteers.

1. Introduction

Humans living in modern societies experience a nightly increase in artificial outdoor light[1] and a daily decrease in natural outdoor light exposure while spending more time indoors.[2,3] Thus, the sharp delineation between day and night existing throughout

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most of our ancestral evolution has changed in industrialized society. More light at night and less light during daytime both negatively impact circadian physiology, well-being and sleep,[4–7] which potentially contributes to the incidence of sick leaves and burnouts at work places in modern societies. For instance, office workers with more light exposure, as indexed by the number of windows at the workplace, tend to have longer sleep duration, better sleep quality, more physical activity and better quality of life compared to office workers with less light exposure.[7] Thus, access to daylight at workplaces represents an important health factor[8] and may also be preventive for the so-called sick building syndrome.[9]

The need for lighting solutions in workplaces and at home, which are tailored to optimally impact on human sleep–wake behaviour and circadian physiology, is starting to be recognized by authorities in industry and in occupational medicine. Several laboratory and field studies have reported beneficial effects of light on daytime cognitive performance and alertness levels.[10–14] While studies in the laboratory included objective measures of daytime cognitive performance and alertness, field studies mostly relied on subjective reports.[15–17] Further, artificial light at the workplace always interferes with natural light,[18] which makes it difficult to quantify the relative contribution of the office lighting solution per se. Even under controlled laboratory conditions, inconsistent data exist, which could not confirm beneficial effects of artificial light on cognitive performance when applied during daytime.[13,19,20] Despite these inconsistences, which are mostly related to differences in the applied lighting solutions and to differences in sleep–wake scheduling, promising results from dynamic light solutions in schools,[21,22] hospitals[23,24] and elderly homes have started to emerge.[25] Since brightness and colour temperature were usually changed simultaneously, it is not yet clear which aspect – the temporal change in colour or in brightness – was more important for the observed effects. It could be, that colour plays an important role at lower ambient light levels, while after passing a certain threshold of brightness its impact is not relevant anymore. At least in elderly homes, the increase in brightness seems to be a rather important aspect to improve mood, circadian physiology and sleep in demented older people.[25–27]

The anatomical and physiological structures underlying light's non-image forming (NIF) effects are based on the non-classical photoreceptive system located in the inner retina, more specifically in the intrinsic photosensitive ganglion cells (ipRGCs) containing the photopigment melanopsin.[28–30] Since maximal response of this NIF system to light occurs between 446 and 483 nm for human melatonin suppression,[31,32] many studies on light's alerting properties had focused on the blue- or melanopic content of light, respectively.[33] Although there is a predominant melanopic contribution to NIF effects in humans, classical photoreception still significantly contributes or modulates NIF effects,[34–36] particularly at lower light intensities < 50 lux, which we usually experience before habitual bedtime.[3] Interestingly, one study reported preliminary evidence for increased heart rate, alertness and reduced alpha EEG activity for both red light (630 nm) as well as for blue light (470 nm).[37]

Recent advances in solid-state LED technology allow tailoring lighting solutions according to 'circadian needs' such as to follow the diurnal dynamics of sunlight during the working day for a given geolocation as well as to implement biologically less active light during nighttime if required. There is emerging evidence that daytime light exposures beneficially impact on sleep and mood in office workers.[7,16] However, it is not yet clear whether modern dynamic LED lighting solutions that change their spectral characteristics across the day

outperform conventional-LED (conLED) solutions in terms of their impact on human well-being, cognition and sleep. Thus, in a first step, we focused on a non-dynamic spectrum and with no change of across the day in this study.

Therefore, we took advantage of a new LED lighting source, which aims at mimicking the spectrum of morning daylight and tested whether it has beneficial effects on visual comfort, melatonin, mood, cognitive performance and sleep in comparison to a conLED lighting solution. The spectrum of morning daylight depends on weather condition, place of measurement (sun or shade), reflections of the environment (e.g. grass, sand, snow) and time. A colour temperature of 4000 K would correspond to a sunny day shortly after sunrise during the so-called 'golden hour' measured in the sun. This is a result based on the simulation tool SMARTS, a 'Simple Model of the Atmospheric Radiative Transfer of Sunshine' that can be found at: https://www.nrel.gov/grid/solar-resource/smarts.html.

Both LED conditions comprised a constant light of 100 photopic lux at 4000 K throughout a normal waking day of 16 hours. However, the spectral components of the two LED light sources used were dissimilar, particularly in the blue and red spectral range as well as with regard to the colour-rendering index (CRI). These spectral differences go along with different responses of the five human light receptors in the eye (cyanopic, melanopic, rhodopic, chloropic and erythropic) without a directly noticeable difference. Visually both spectra when viewed directly or on a white surface appeared similar, and the difference in spectral composition can only become visible when the light is reflected by a coloured surface (e.g. cyan or red coloured objects can look more saturated under daylight LED (dayLED)). Nevertheless the relevance of the interaction of the five photoreceptors for both, visual and non-visual light responses is not yet fully understood.

We hypothesized that in comparison to the conLED, the dayLED lighting solution leads to better visual comfort, better alertness, better cognitive performance levels and better sleep without affecting circadian melatonin profiles – a marker of the human circadian timing system.

2. Method

2.1. Participants

After written informed consent, 15 healthy male volunteers (age range: 19–32 years, mean age: 23.2 ± 4.3 years) successfully completed the study and received monetary compensation for participation. The study protocol, screening questionnaires and consent form were approved by the local ethics committee and conformed to the Declaration of Helsinki. All study participants had a good sleep quality as assessed with the Pittsburgh Sleep Quality Index (PSQI score ≤ 5) and were not extreme chronotypes (>2 and <7 points on the Munich Chronotype questionnaire). They underwent a medical examination carried out by the physician in charge and an ophthalmic examination by a certified optometrist to exclude volunteers with visual impairments. Participants were not excluded if they wore glasses or contact lenses. Before the experiment they performed the 'Ishihara Test' for colour deficiency.[38] Exclusion criteria were smoking, medication or drug consumption, shift work within the last three months and transmeridian flights up to one month prior to the study. During the entire study protocol, which comprised a total of 2–3 weeks, participants were instructed to keep a regular sleep–wake schedule (bed times and wake times within 60 minutes of self-selected target time). Compliance was verified by sleep logs and ambulatory activity measurements (Actiwatch-L, Cambridge Neurotechnology, Cambridge, UK). Actimetry-derived sleep duration was on average 7 hours and 26 minutes prior to the in-laboratory part of the

study, with an average sleep start time at midnight (00:01 h).

2.2. Study design

The study was carried out at the Centre for Chronobiology in Basel, Switzerland, between the beginning of June 2015 and the beginning of October 2016. The 'in-laboratory part of the study' comprised two 49-hour episodes, which participants spent in sound-attenuated chronobiology suites under light, temperature and humidity controlled conditions (Figure 1). Volunteers reported to the laboratory 6 hours prior to their usual bedtime, electrodes for polysomnographic recordings (PSG) were attached, cognitive test batteries explained and practiced during the first evening under standard fluorescent lighting conditions (Philips Master TL5 HO 54W/830, CRI 80, 3000 K, 100 lux, at the participant's eye level in bed facing the opposite wall). After an 8-hour sleep episode baseline (BL) night, scheduled at their habitual bedtimes, volunteers either woke up in to the dayLED condition (Toshiba TRI-R Circadian System NP10576, based on TRI-R LED SMD5056) or in to the conLED, T5-1200 LED TUBE, based on conventional white LED SMD2835) condition for 16 hours, followed by a second 8-hour sleep episode (i.e. treatment (TR) night) and a final 11-hour episode of scheduled wakefulness (treatment day 2). During wakefulness volunteers were allowed to move freely in their room when they were not involved in scheduled tasks. They were allowed to read and listen to music but were not allowed to use electronic devices such as mobile phones and tablet PCs. They received the same scheduled meals (25 minutes, 4 hours and 11 hours after wake up). The order of the lighting conditions (dayLED and conLED) was counterbalanced, such that half of the participants started with dayLED and vice versa. The washout period between the two in-lab sessions was one week.

2.3. Lighting

Both light sources, the dayLED and the conLED were placed in standard fixtures in the ceiling of the back wall in the chronobiology room and emitted light indirectly into the rooms, which were coated with white wallpaper. We measured the photopic lux at the eye level, when the volunteer was lying in bed at a fixed position gazing at the back wall
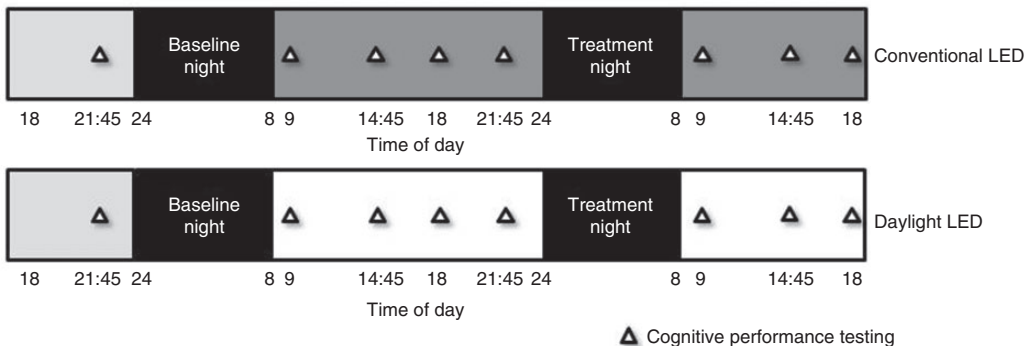

Figure 1 The study protocol consisted of two 49-hour blocks either under the conLED (upper graph) or dayLED condition (lower graph) in a balanced crossover within subject design. Both blocks started 6 hours prior to habitual bedtime under fluorescent light. The baseline (BL) and treatment (TR) nights are delineated with black bars, and the triangles indicate the timing of the cognitive test batteries. Saliva for melatonin assays and subjective sleepiness and mood ratings were collected in half-hourly intervals in the mornings and evenings but at 1- or 2-hourly intervals during daytime. For further details please refer to the text

of the room. Illuminance at this position was 100 lux at 4000 K for both the dayLED and conLED condition. However, the spectral composition of the two LED types was different as illustrated in the upper panel of Figure 2. The blue peak in the conLED was more pronounced at 450 nm as compared to a smoother spectrum of the dayLED. The dayLED had a higher spectral irradiance below 440, between 460 and 520 and over 620 nm, so it was more closely matched to daylight.[39]
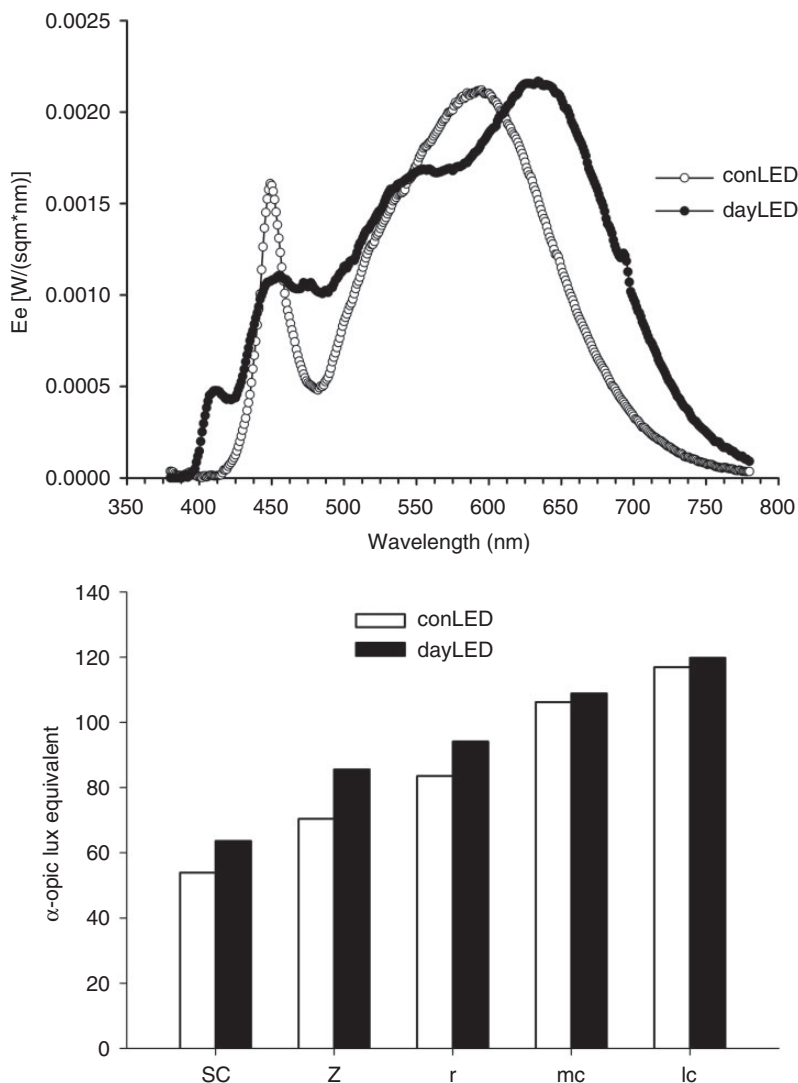

Figure 2 During the conLED and dayLED conditions, the study volunteers were exposed to the same illuminance (100 lux) and colour temperature (4000 K). However, the relative spectra (upper panel) of the dayLED and conLED differed, so the colour rendering index (CRI) and the melanopic strength differed as well. The lower panel shows the stimuli delivered to the five different types of retinal photoreceptor[40] in the conLED and dayLED conditions (sc: S cones, z: ipRGC, r: Rods, mc: M cones, lc: L cones)

Calculating the melanopic lux according to Lucas *et al.*[40] resulted in 84.1 melanopic lux for the dayLED and 69.1 melanopic lux for the conLED. Thus, the melanopic strength was 21% higher for the dayLED than the conLED. Furthermore, the CRI was also higher for dayLED (99) compared to conLED (79) – 25.3% higher for the dayLED than the conLED. A newer system for evaluating a light source's colour rendering properties is IES TM-30-15. The fidelity index and the gamut index of IES TM-30-15 for dayLED was $Rf = 97$ and $Rg = 101$, respectively, and for conLED it was $Rf = 81$ and $Rg = 94$. Because the interaction between visual and non-visual responses is not yet completely understood, the lower panel of Figure 2 shows the stimulus delivered to the five light receptors in the human eye. However, spectral power distribution and the response of the human light receptors alone do not yet allow for estimation of human responses. A way to estimate human responses to light (i.e. melatonin suppression) has been proposed by Rea *et al.*[41] They propose to use a response function combining the non-visual systems and the visual systems eventually calculating the so-called circadian stimulus (CS). Using their response function results in a CS of 0.097 for the dayLED and a CS of 0.17 (75% higher) for the conLED condition.

2.4. Polysomnographic recordings

Sleep EEG activity was continuously recorded during the scheduled sleep episode with the Vitaport Ambulatory system (Vitaport-3 digital recorder TEMEC Instruments BV, Kerkrade, the Netherlands). Twelve EEG derivations (Fz, F3, F4, Cz, C3, C4, Pz, P3, P4, Oz, O1, O2) referenced against linked mastoids (A1 and A2), two electrooculograms, one submental electromyogram and one electrocardiogram were recorded. All signals were low pass filtered at 30 Hz (fourth-order Bessel type anti-aliasing, total 24 dB/Oct) at a time constant of 1 second. After online digitization by using a 12 bit AD converter ($0.15 \mu V/bit$) and a sampling rate at 128 Hz for the EEG, the raw signals were stored on a flash RAM card and later downloaded to a PC hard drive. Sleep stages were visually scored per 30-second epochs by two experienced polysomnography technicians blind to the light conditions according the standard criteria.[42] Non-rapid eye movement sleep (NREMS) was defined as the sum of NREM stages 2, 3 and 4. Slow wave sleep (SWS) was defined as the sum of NREMS stages 3 and 4. Spectral analysis was conducted using a fast Fourier transformation (FFT; Hanning 4-second window, 50% overlapped), which yielded a 0.25 Hz bin resolution. EEG power spectra were calculated during NREMS in the frequency range from 0 to 32 Hz. Artefact-free 4-second epochs were averaged across 30-second epochs. Here we report EEG data for frontal (F3, F4) derivations, in the frequency range of 0.75–20 Hz.

2.5. Melatonin

Saliva collections were scheduled every 30 minutes in the morning and evening and every 1 or 2 hours in between (for precise timing see timing of subjective sleepiness ratings below). A direct double-antibody radioimmunoassay was used for the melatonin assay (validated by GC-MS with an analytical least detectable dose of 0.65 pg/ml; Bühlmann Laboratory, Schönenbuch, Switzerland).[43] The minimum detectable dose of melatonin (analytical sensitivity) was determined to be 0.2 pg/ml.

2.6. Cognitive performance and subjective variables

Cognitive performance was assessed four times during the 16 hours of scheduled wakefulness starting 70 minutes after lights on in the morning and then every four hours thereafter. The volunteers did all the testing in front of a grey computer screen, which

emitted around 85 photopic lux for both lighting conditions. Thus, the lighting situation during testing was rather uniform for both light. Among various subjective variables, the 35-minute cognitive test battery included a visual verbal n-back task and an auditory sustained attention task (i.e. psychomotor vigilance task, PVT).

2.6.1. Working memory performance (n-back paradigm)

In the n-back task, participants indicated, using the keyboard, whether the displayed letter matches the target stimulus presented n trials ago (n-back level). The sequence was generated immediately prior to presentation using letters randomly drawn from nine phonologically dissimilar consonants and had 11 targets (i.e. 'yes' responses). Letters were printed in a white colour on a grey screen. Each session consisted of six blocks that were divided into two bouts with an approximate time on task of 12 minutes per session (i.e. 48 blocks in total per light condition). The demand level (i.e. the working memory load) was adjusted to the individual performance of the participant using an adaptive version of the task. Each session started with n-back level = 1 and the n-back level of the remaining five blocks depended on the performance of each preceding block: $n + 1$, if the proportion of correct responses was above 90% (i.e. ≤ 3 mistakes), and $n-1$, if the proportion of correct responses ([Hit+Correct Rejection]/32) was equal to or below 70% (>10 mistakes) and remained the same between these parameters.[44] Each block consisted of $32 + n$ trials (stimulus duration: 500 ms; interstimulus interval: 1.500 ms, response time 1.000 ms). A brief practice episode with the n-back level of the forthcoming block preceded each block (two targets included), so that the participants were able to familiarize themselves with the n-back level.

2.6.2. Psychomotor vigilance performance task

PVT is a sustained attention performance task sensitive to circadian rhythmicity and sleep need.[45] Participants were requested to press a response button as fast as possible as soon they heard an auditory stimulus while also avoiding to press the button too soon. The auditory stimulus was presented in intervals randomly varying from 2 to 9 seconds. The duration of the task was 10 minutes. Participants used the same desktop computer during one session.

2.6.3. Subjective sleepiness and visual comfort

Participants rated their sleepiness levels regularly on the Karolinska Sleepiness Scale (KSS)[46] throughout the entire laboratory stay. The intervals were as follows: half hourly intervals in the morning at lights on until three hours after and in the evening starting five hours prior to lights off. For the remainder of scheduled wakefulness the KSS was assessed in hourly or two hourly intervals. At the same intervals, participants rated also their level of alertness, mood, stress, relaxation and physical comfort on the visual analogue scale (VAS) described earlier.[47] This method is used to measure subjective sensations on a visual scale from 0 to 100. Compared to categorical scales this form has been chosen because it is more suitable for continuous variables (alertness, mood, etc.) and even the slight differences in response behaviour can be measured. To assess each participant's subjective perception of visual comfort, we used a five-point Likert type scale that probed brightness, light colour and glare perception based on a selection of questions derived from Eklund and Boyce.[48]

2.7. Statistical analysis

Statistical analyses were performed using SAS (version 9.4; SAS Institute, Cary, NC). All output variables of the 15 men were statistically analysed with mixed-model analyses of

variance (PROC MIXED) with main repeated factors being 'light condition' (dayLED and conLED) and 'time of day' (time points) and subjects as a random factor with a combined unstructured and autoregressive covariance structure according to Kincaid.[49] For PVT performance, the default performance metrics – median reaction time (RT), 10% fastest and 10% slowest RT and lapses were calculated according to Blatter et al.[45] Response times below 100 ms were considered as false starts and therefore excluded. For n-back performance, the following metrics were used: the number of hits (i.e. target present and response 'yes'), false alarms (i.e. target not present and response 'yes'), accuracy (hits – false alarms) and the percentage of correct responses. Visually scored sleep stages were expressed as percentages of total sleep time (TST). All-night EEG power density in NREMS was analysed for frontal derivations for each 0.25 Hz frequency bin, with the main factor 'light condition'. NREM-REMS cycles were defined according to Feinberg and Floyd.[50] Thereof, each sleep cycle was subdivided into 10 time intervals of equal length during NREMS and into four time intervals during REMS.

3. Results

3.1. Visual comfort

Subjects rated visual comfort (i.e. the combined items brightness and colour temperature) as significantly better during the dayLED than the conLED condition (Figure 3, factor 'light condition': $F_{1,14} = 4.9$, $p < 0.04$), while the factors 'time of day' and the interaction term 'light condition' × 'time of day' were not statistically significant.

3.2. Melatonin

The typical diurnal melatonin profile was observed during both the dayLED and the conLED condition without any statistically significant effects other than time of day
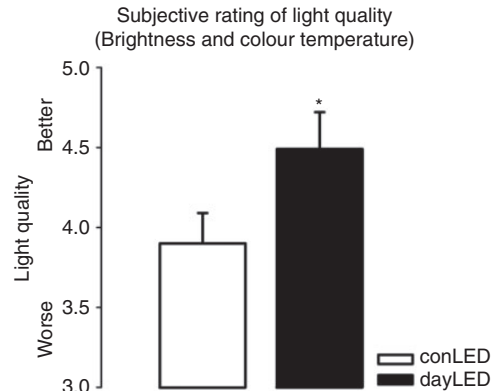

Subjective rating of light quality
(Brightness and colour temperature)

Figure 3 Mean visual comfort for the combined items 'brightness and colour temperature perception' under the conLED and the dayLED conditions (better light quality going up on the y-axis, mean values, n=15, + SEM). Asterisk indicates a significant difference ($p < 0.02$)

effects (Figure 4, $F_{1,41} = 9.55$, $p < 0.0001$). The evening increase in melatonin occurred 2–3 hours before habitual bedtime, which indicates normal circadian entrainment at the start of the in-laboratory part of the study.

3.3. Subjective mood/well-being

There was a significant diurnal time course of subjective mood/well-being ratings ($F_{1,40} = 1.59$, $p < 0.02$) without a significant effect of the factor 'light condition' (Figure 5). However, the interaction term 'light condition' and 'time of day' yielded a significant effect ($F_{1,30} = 1.7$, $p < 0.02$), such that participants felt happier during the morning and evening in the dayLED compared to the conLED condition.

3.4. Subjective sleepiness

The diurnal time course with higher sleepiness levels in the morning, due to sleep inertia and higher sleepiness levels in the evening due to increasing sleep pressure and the attenuation of the circadian wake drive, was present in both LED conditions (Figure 6, factor 'time of day', $F_{1,40} = 5.82$, $p < 0.0001$).
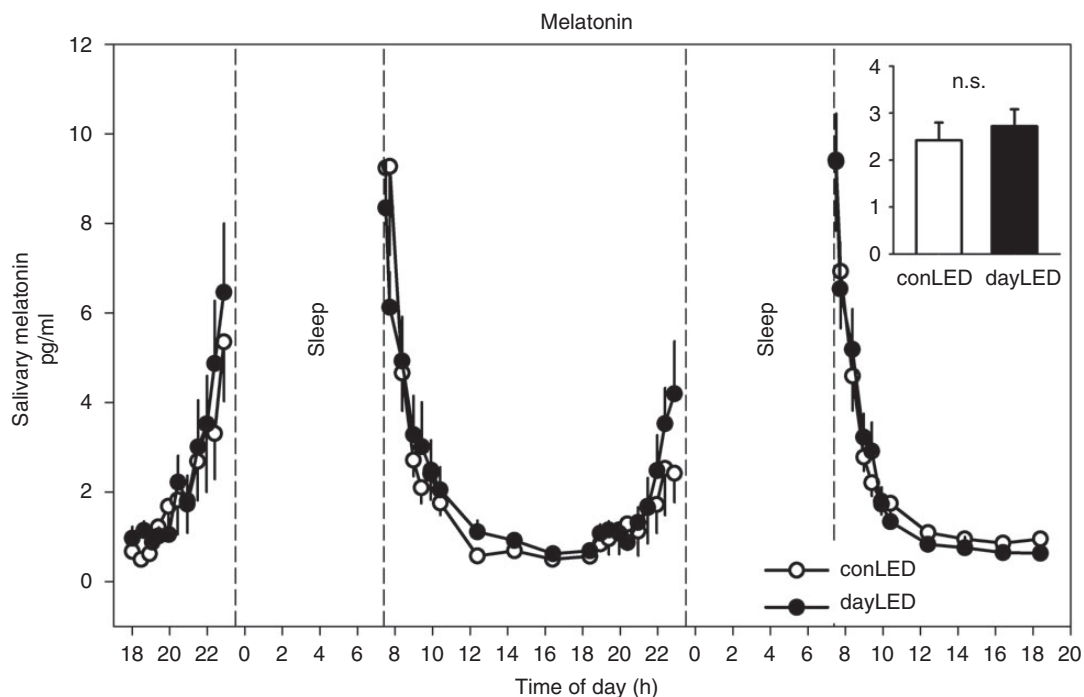
Figure 4 Time course of the diurnal salivary melatonin profile under the conLED and dayLED conditions in pg/ml plotted against relative clock time in hours (i.e. average clock times according to the participant's habitual bedtimes; mean values, n=15,±SEM). Inset in the upper right corner illustrates time averaged values and SEM for both the conLED and dayLED conditions (n.s. = not significant)

Furthermore, the main effect 'light condition' yielded significance with higher alertness (i.e. lower sleepiness) levels for the dayLED compared to the conLED condition (Figure 6, inset, $F_{1,40}=12.3$, $p < 0.001$). Although most of the alerting effect observed under dayLED occurred in the morning during sleep inertia, post hoc tests were not performed due to the lack of a significant interaction term 'light condition' × 'time of day'.

3.5. Psychomotor vigilance performance (PVT)

Neither median RT, the 10% slowest or 10% fastest reactions times nor the performance lapses yielded any statistically significant effects of 'light condition', 'time of day' or its interaction. The time course of PVT performance was rather stable across the entire

in-laboratory day during both light conditions (i.e. no time of day effect).

3.6. Working memory performance (n-back)

None of the conventional metrics yielded statistically significant light effects. Further, no 'time of day effect' and no significant interaction term between the two main factors were found (data not shown).

3.7. Sleep stages

Table 1 summarizes all sleep variables derived from visual inspection of the PSG during the BL and treatment nights for both LED conditions. Overall, no significant effect of 'light condition' was found for any of the sleep stages. The factor 'night' (BL and treatment night) yielded significance for sleep latency, stage 2 and REMS ($p < 0.05$ at
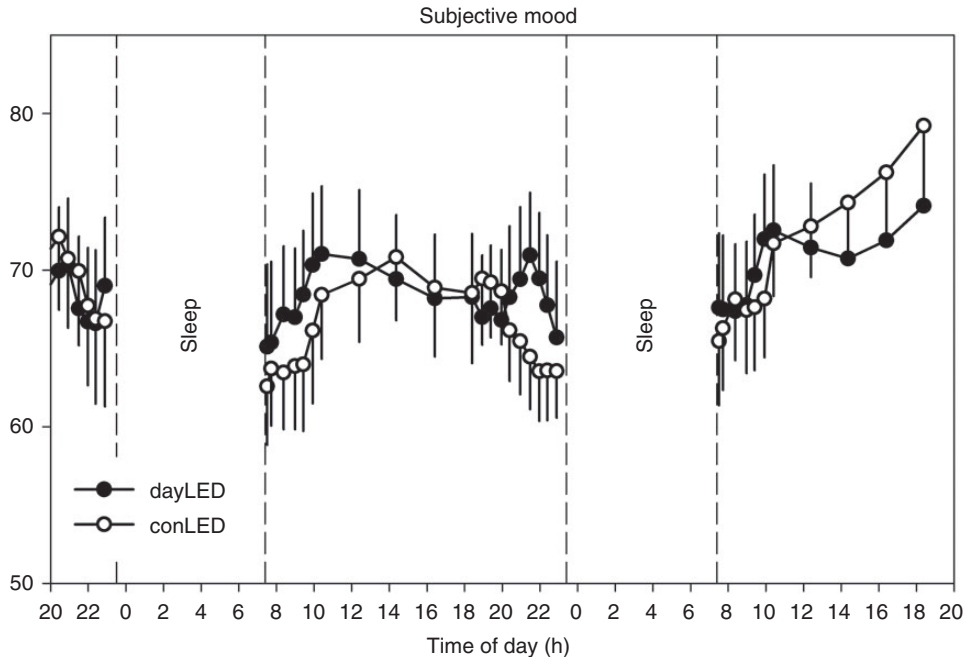
Figure 5 Time course of diurnal mood ratings on a visual analogue scale (better mood going up) under the conLED and dayLED conditions plotted against relative clock time in hours (i.e. average clock times according to the participant's habitual bedtimes; mean values, n=15, ± SEM)

least) indicating a general decrease in sleep latency, stage 2 and a general increase in REMS from the BL to the treatment night independent of the light condition. REMS and NREMS yielded a significant interaction 'light treatment' × 'night', and post hoc comparisons indicated a significant increase in REMS from BL to the treatment night at the expense of NREMS only during the conLED condition ($p < 0.03$ at least). Direct post hoc comparisons between dayLED and conLED did not reveal any significance for both the BL and the treatment night respectively.

3.8. EEG power density

EEG power densities during NREMS for both light conditions were not significantly different between dayLED and conLED, when expressed relative to the BL nights (Figure 7) in none of the frequency bins

between 0.75 and 20 Hz. Post hoc comparison for each light conditions separately yielded significant increases for the dayLED in the low delta band (1.0–1.75 Hz), the high theta band (7.5–8.0 Hz) and significant decreases in the sigma band 11.75–14 Hz, while for the conLED a significant increase in the theta-alpha band was found (5.75–9.5 Hz). The temporal dynamics of relative EEG delta activity exhibited the usual decline across the night with an superimposed ultradian NREM-REMS cycling during the BL nights and both treatment nights, dayLED and conLED (Figure 8, $F_{1,39} = 15.98$, $p < 0.0001$). The interaction 'light condition' × 'night' was significant ($F_{1,39} = 166$; $p < 0.009$), and post hoc comparisons indicated significantly higher EEG delta activity during the dayLED compared to conLED in the first NREM and last NREM episode (p at least 0.035).
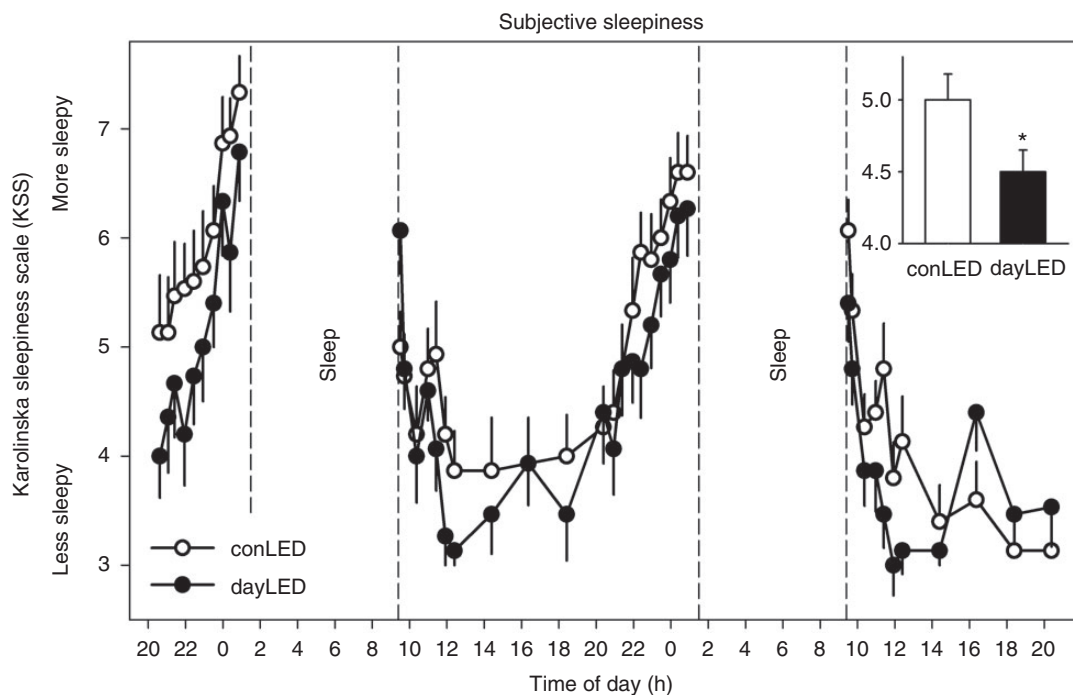
Subjective sleepiness

Figure 6 Time course of diurnal sleepiness ratings on the Karolinska Sleepiness Scale (sleepier going up) under the conLED and dayLED conditions plotted against relative clock time in hours (i.e. average clock times according to the participant's habitual bedtimes; mean values, n = 15; ± SEM). Inset in the upper right corner illustrates time averaged values and SEM for both the conLED and dayLED conditions (asterisk indicates a significant difference, $p < 0.002$)

4. Discussion

Here we report the first evidence that a LED light source, spectrally tuned to be closer to natural morning daylight then a conLED, has beneficial effects on visual comfort and NIF outcomes such as alertness and human sleep. Which specific characteristic of the LED spectrum was most relevant to elicit the observed effects in our study is difficult to identify. The smooth dayLED spectrum did not only differ from the conLED in the blue but also in the longer-wavelength portion of the visible spectrum (see Figure 2). We did not observe significant changes in the diurnal profile of melatonin secretion in our study. Since the dayLED had 21% more melanopic strength than the conLED, a stronger attenuation of the evening increase in melatonin

along with subjective sleepiness could have been anticipated. In contrast, visual inspection and a post hoc comparison of the average evening melatonin values prior to the treatment night yielded lower values in the conLED than the dayLED condition, indicating either more melatonin suppression or a phase delay of the circadian melatonin rhythm during conLED compared to dayLED. Later, we could not test since the dim light melatonin onset was masked by our lighting situation. Interestingly, the alerting effects of dayLED did not occur in the evening but in the morning. It is tempting to say that the morning dayLED with 4000 K and 100 photopic lux was probably most efficient in the morning- or the other way around that LEDs with a prominent blue peak, such as the conLED, do not have strong

Table 1 Sleep parameters of the baseline and treatment nights based on visual scoring for the dayLED and the conLED condition

Light condition Night	conLED Baseline	dayLED Baseline	conLED Treatment	dayLED Treatment	Factor Light	Factor Night	Factor Light × Night	Post hoc
Sleep Variables (n=15)								
Total Sleep Time (hours)	7.5±0.08	7.5±0.1	7.4±0.1	7.3±0.1	n.s	n.s	n.s	
Sleep Efficiency (%)	93.4±1.0	93.5±0.7	92.1±0.8	91.4±1.3	n.s	n.s	n.s	
Wake (%)	7.2±1.3	7.1±0.9	8.6±1.0	9.8±1.7	n.s	n.s	n.s	
Stage 1 (%)	8.7±0.7	8.4±0.6	8.2±0.8	9±0.8	n.s	n.s	n.s	
Stage 2 (%)	52.7±2.0	50.4±1.5	49.3±1.6	48.3±1.8	**n.s**	$F_{1,11}=6.3$; $p=0.03$	**n.s**	Baseline vs Treatment
Stage 3 (%)	7.4±0.8	8.1±0.8	6.7±0.6	8.9±1.3	n.s	n.s	n.s	
Stage 4 (%)	11.1±1.6	10.5±1.6	12.1±1.8	11.8±2.0	n.s	n.s	n.s	
REM Sleep (%)	20±1.1	22.6±0.8	23.8±1.1	22.1±0.8	**n.s**	0.02	$F_{1,19.5}=8.8$; $p=0.007$	conLED_base vs conLED_treat
Slow wave sleep (%)	18.6±1.3	18.6±1.4	18.7±1.7	20.6±1.9	n.s	n.s	n.s	
NREM sleep (2,3,4 %)	71.3±1.2	69±0.9	68±1.3	69±1.1	**n.s**	0.07	$F_{1,19.5}=6.3$; $p=0.02$	conLED_base vs conLED_treat
Sleep Latency 1 (min)	10.4±3.0	8.7±2.1	16.6±4.2	12.7±3.1	n.s	n.s	n.s	
Sleep Latency 2 (min)	14.8±3.7	14±2.6	21.8±4.7	18.1±3.3	n.s	n.s	n.s	
REM Sleep Latency (min)	89.7±12.4	94±11.1	89.7±12.4	88.3±8.8	n.s	n.s	n.s	

Sleep parameters are averaged separately across the baseline night and the recovery night (mean±SEM) for the dayLED and conLED condition separately. TST: total sleep time; SE: sleep efficiency (TST/Time in Bed (TIB)×100); WAKE: wake after lights off (in % of TIB between lights off and lights on); Sleep latency 2: time between lights off and the first occurrence of stage 2; REM Sleep Latency: time between lights off and the first occurrence of stage REM; Slow wave sleep: sum of stages 3 and 4 in % of TST; NREM sleep: sum of sleep stages 2–4 in % of TST; REM: REM sleep in % of TST. The columns with the factors 'Light', 'Night' and their interaction depict significant influences derived from mixed-model analyses of variance. Post hoc testing is reported in the last column (for more details, see text). n.s.: not significant.
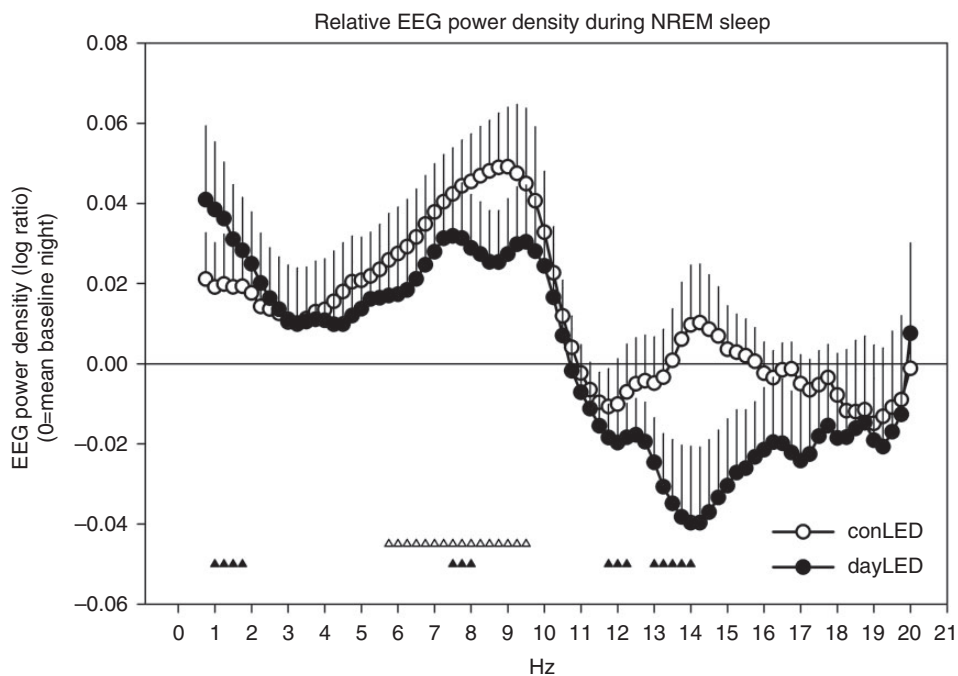
Relative EEG power density during NREM sleep

Figure 7 Relative EEG power density during non-rapid eye movement sleep in the treatment (TR) night for the conLED and the dayLED conditions expressed relative to the baseline (BL) night (log ratio) in the frequency range of 1 to 20 Hz in the frontal EEG derivation F3 (mean values, n=15; ± SEM). The triangles indicate frequency bins for which a significant difference from the baseline night ($p < 0.05$) was found for each lighting condition separately

alerting properties in the morning. Interestingly, also Gabel *et al.*[12] did not observe an alerting response to monochromatic blue light at 460 nm in the morning, while such a response was clearly evident in the evening and at night.[51,52] Thus, evening and nighttime hours represent a time window during which blue light's alerting capacity seems to be stronger than during morning hours. Indeed, there is mounting evidence that light's alerting action is time of day dependent.[13,14,20] Further, there is a lack of an action spectrum for the human alerting response to light as well as consistent data on time of day dependent effects. Thus, it is not yet clear where in the 'blue range' the maximal alerting response can be achieved. There have been discussions that different from the human action spectra for melatonin suppression between 446 and

483 nm,[31,32,53] the peak sensitivity for the alerting response could be lower between 400 and 440 nm in the cyanopic range.[54] The fact that our dayLED emitted more light in the cyanopic range could also explain its stronger alerting effect compared to conLED. Further, the CS for dayLED was 75% lower than for conLED, from which one could conclude that conLED would provide a much stronger stimulus to the circadian system along with stronger alerting effects. This was not the case.

Subjective alertness levels are certainly not only driven by environmental light (for a review see Cajochen *et al.*[55]) but also influenced by subjective aspects such as well-being[47] and visual comfort.[56] The influence of visual comfort on eye strain and fatigue has been recognized in research on recommendations of comfortable visual display terminal
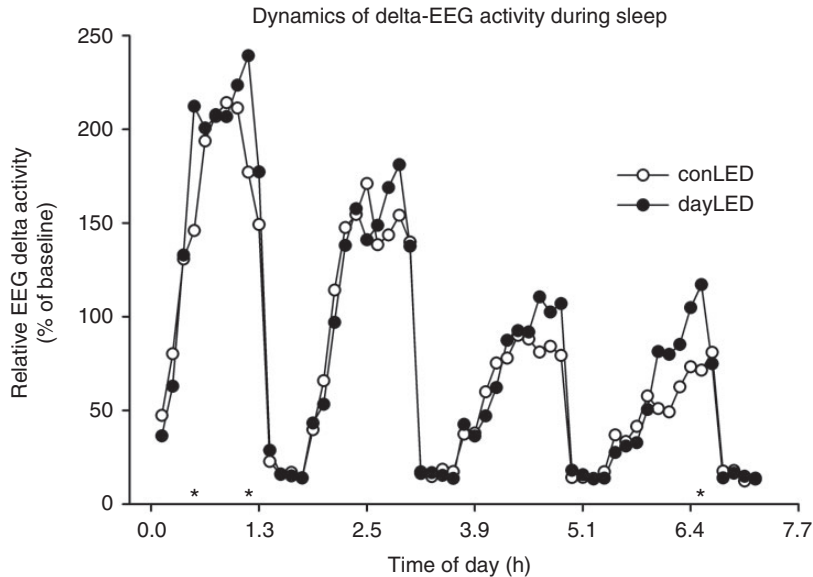
Dynamics of delta-EEG activity during sleep

Figure 8 Temporal dynamics of relative EEG delta activity (0.75–4.5 Hz) during the treatment (TR) night for the conLED and the dayLED condition expressed relative to the baseline (BL) night in the frontal EEG derivation F3 (mean values, n=15; ±SEM). Asterisks indicate significant post hoc comparisons between the conLED and dayLED condition. For further information see text

workstation design – an important aspect of visual ergonomics.[57] This needs to be extended into studies looking at the interplay between the visual and non-visual effects of lighting solutions on human cognitive performance and sleep. The observed better visual comfort under the dayLED condition could very well be due to the rather smoother light spectrum of the dayLED, which also resulted in a better colour rendering (both better CRI and better IES TM-30-15 metrics). Better colour rendering facilitates perception of colours (e.g. skin tone, furniture, food) more naturally. Thus, the observed better visual comfort during dayLED per se could have led to better alertness and mood particularly in the morning and evening hours. This corroborates a finding by Shamsul et al.,[56] who tested three different colour temperatures (2700, 4000 and 6200 K all at 400 lux) in a workplace setup in the laboratory and found better typing performance along with more alertness and visual comfort under both the 4000 and 6700 K condition compared to the 2700 K condition.

Recent insights from animal data reveal interesting visual features of the so far considered non-visual pathway of light to the suprachiasmatic nuclei (SCN), the central circadian pacemaker, as the main target. Melanopsin signals also reach brain regions responsible for form vision,[58–60] and recent data clearly indicate that melanopsin contributes to the representation of images in the early visual system.[61] This underscores the dual role of the vertebrate eye: a classical light detection for image forming vision and a variety of physiological and behavioural functions, known as NIF functions, which are distinct from sight. In addition to the SCN and the early visual system, the ipRGCs target also a wide range of brain regions (for a review see Schmidt et al.[62]) implicated in the regulation of a number of behavioural

and physiological functions which have a major impact on our health and well-being.

It is difficult to relate the observed changes to a distinct difference in the LED spectrum, the higher melanopic strength, the better CRI or just the better visual and thus subjective overall feeling under such a high-end LED solution. Thus, in a next step it would be interesting to compare which of these proposed potential causes is the most important for a dayLED solution at the workplace. Studies on the impact of light with a fuller spectrum compared to (more energy efficient) standard artificial lighting with line or band spectra are rare and go back to the 1980s with inconclusive and controversial findings. These studies were conducted under fluorescent lighting. Some studies find statistically significant improvements under full-spectrum lighting, such as less fatigue and better visual acuity[63] while others fail to find any effects.[64,65] Positive impacts of full-spectrum light on health in primary schools were demonstrated by the lower number of absences compared to other types of lighting.[66] However, the methodology of this study was critically reviewed by Veitch and McColl, who state that it was not clear whether the beneficial effects were only attributable to the lighting situation.[67] It must be noted that full-spectrum fluorescent lighting does not have a continuous spectrum, as occurs in natural daylight or incandescent light, but only a 'fuller' spectrum than a conventional fluorescent tubes. Furthermore, those full spectrum lamps are also characterized by the fact that their colour temperature is higher than 5000 K, and that a UV component is included.

In summary, we have evidence for beneficial effects of a morning dayLED on alertness and sleep under stringently controlled laboratory conditions in healthy normal good sleepers, who had very good cognitive skills. Since dayLED outperformed conLED in healthy good sleepers, it is tempting to say that people with insufficient sleep may profit even more from a dayLED solution at their workplace.

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