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# Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance

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**Cajochen C, Frey S, Anders D, Späti J, Bues M, Pross A, Mager R, Wirz-Justice A, Stefani O.** Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance. *J Appl Physiol* 110: 1432–1438, 2011. First published March 17, 2011; doi:10.1152/japplphysiol.00165.2011.—Many people spend an increasing amount of time in front of computer screens equipped with light-emitting diodes (LED) with a short wavelength (blue range). Thus we investigated the repercussions on melatonin (a marker of the circadian clock), alertness, and cognitive performance levels in 13 young male volunteers under controlled laboratory conditions in a balanced crossover design. A 5-h evening exposure to a white LED-backlit screen with more than twice as much 464 nm light emission {irradiance of 0,241 Watt/(steradian $\times$ m$^2$) [W/(sr $\times$ m$^2$)], $2.1 \times 10^{13}$ photons/(cm$^2$ $\times$ s), in the wavelength range of 454 and 474 nm} than a white non-LED-backlit screen [irradiance of 0,099 W/(sr $\times$ m$^2$), $0.7 \times 10^{13}$ photons/(cm$^2$ $\times$ s), in the wavelength range of 454 and 474 nm] elicited a significant suppression of the evening rise in endogenous melatonin and subjective as well as objective sleepiness, as indexed by a reduced incidence of slow eye movements and EEG low-frequency activity (1–7 Hz) in frontal brain regions. Concomitantly, sustained attention, as determined by the GO/NOGO task; working memory/attention, as assessed by "explicit timing"; and declarative memory performance in a word-learning paradigm were significantly enhanced in the LED-backlit screen compared with the non-LED condition. Screen quality and visual comfort were rated the same in both screen conditions, whereas the non-LED screen tended to be considered brighter. Our data indicate that the spectral profile of light emitted by computer screens impacts on circadian physiology, alertness, and cognitive performance levels. The challenge will be to design a computer screen with a spectral profile that can be individually programmed to add timed, essential light information to the circadian system in humans.

nonvisual effects of light; spectral analysis; shift work; melatonin; alertness

THE WORLD IS ONLINE. Over 2 billion people use the internet, and this number is rapidly increasing. In 2010, 1.6 billion computers, television sets, and cellular phones were sold globally (www.worldometers.info), which illustrates the numbers of individuals who spend time in front of computer screens, video game consoles, or other video monitors. Newer computers and TV screens are now frequently equipped with light-emitting diodes (LED), which peak in the short-wavelength region (i.e., the blue range at ~460 nm). There is ample evidence that a novel, short-wavelength-sensitive photoreceptor system is primarily responsible for a variety of nonvisual light responses, in particular, resetting the timing of the circadian pacemaker, suppressing melatonin production, improving alertness and performance, and elevating brain activation, as assessed from EEG-derived correlates of arousal (5, 6, 8, 17, 18, 24, 28, 31). Furthermore, bright light exposure and exposure to monochromatic blue light in the evening lengthens sleep latency and reduces initial EEG delta activity, a marker of slow-wave sleep (7, 20). Thus the frequent use of LED sources could have ramifications on human behavior, since light is the most important synchronizer of our biological clock. The circadian pacemaker responds differentially to the resetting effects of light, depending on the circadian phase of light exposure. Phase delays occur when light exposure is centered prior to the core body temperature minimum, whereas circadian-phase advances can be elicited by light exposures centered after the core body temperature minimum, which normally occurs in the second half of the biological night (14). This means that exposure to artificial light in the evening, when our circadian timing system is most vulnerable to light, has the capacity to modify rhythms and thus sleep and neurobehavioral function. While acute light exposure in the evening may, for instance, help night workers to become more alert and perform better, the repercussions of chronic, inappropriate-timed exposure could lead to circadian misalignment and thus eventually to sleep problems (23), depression (19), and even the cardiovascular diseases seen in shift workers (27).

Here, we investigated the impact of a LED-backlit computer screen (enhanced in the short-wavelength region, i.e., 460 nm) in comparison with a LED-free computer screen on a wide range of measures in human physiology and behavior, such as melatonin levels, cognitive performance, and the EEG during wakefulness. Our main prediction was that a 5-h evening exposure to a LED-backlit computer screen, in comparison with a non-LED computer screen, would suppress the evening increase in melatonin levels and evoke an alerting response with concomitant improvement in cognitive performance.

## METHODS

Healthy, young male volunteers (19–35 years) were recruited via advertisements at the University of Basel (Switzerland). Potential study participants filled out questionnaires about their general health, sleep quality [Pittsburgh sleep quality index (PSQI)], and sleep-wake behavior [Munich chronotype questionnaire (MCTQ) (34)]. Volunteers with good sleep quality (PSQI score $<5$), no extreme chronotype ($>3$ and $<6$ points on the MCTQ questionnaire), and good general health underwent a medical examination carried out by the physician in charge and an ophthalmologic examination by a certified optometrist to exclude volunteers with visual impairments, such as color blindness, diminished pupil

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reaction to light, and a reduced visual field. Participants were not excluded if they wore glasses or contact lenses. Exclusion criteria were smoking, medication or drug consumption, shift work within the last 3 mo, and transmeridian flights up to 3 mo prior to the study. Thirteen volunteers (mean age: 23.8 years ± 5.0 SD; mean body mass index: 22.6 ± 1.7 SD) were then selected for the study. All subjects gave written, informed consent. The study protocol, screening questionnaires, and consent form were approved by the local ethics committee and conformed to the Declaration of Helsinki.

During the entire study protocol, which comprised a total of 2 wk, participants were instructed to keep a regular sleep-wake schedule (bed times and wake times within ±30 min of self-selected target time). Compliance was verified by sleep logs and ambulatory activity measurements (Actiwatch-L, Cambridge Neurotechnology, Cambridge, UK). The "in laboratory" part of the study was carried out in Switzerland between the end of September and beginning of November. In a 25-$m^2$ room, two cubicles were installed in such a way that they were completely light shielded, and only the light emitted by the computer screen fell onto the volunteers' eyes at a distance of ~60 cm. Two different computer screens were compared: a LED-illuminated liquid crystal display screen (HP LP2480zx) and a cold cathode fluorescent lamp (CCFL)-illuminated screen (HP LP2475w), both with a screen diagonal of 24 in. and a resolution of 1920 × 1200 pixels adjusted to the identical luminance of 250 nits (nits as 1 cd/$m^2$). Spectral measurements were carried out using a Konica Minolta CS-1000 (Konica Minolta Sensing, Osaka, Japan). Both computer screens were set to a white background with a color temperature of 6,953 K for the LED-illuminated and 4,775 K for the CCFL-illuminated screen, thus reducing the amount of blue light from one-half to approximately one-third in the LED compared with the non-LED, CCFL-illuminated screen. The irradiance between 400 nm and 480 nm of the LED-illuminated computer screen was 0,241 Watt/(steradian × $m^2$) [W/(sr × $m^2$)] and 0,099 W/(sr × $m^2$) for the non-LED, CCFL-illuminated computer screen (Fig. 1). Although the difference

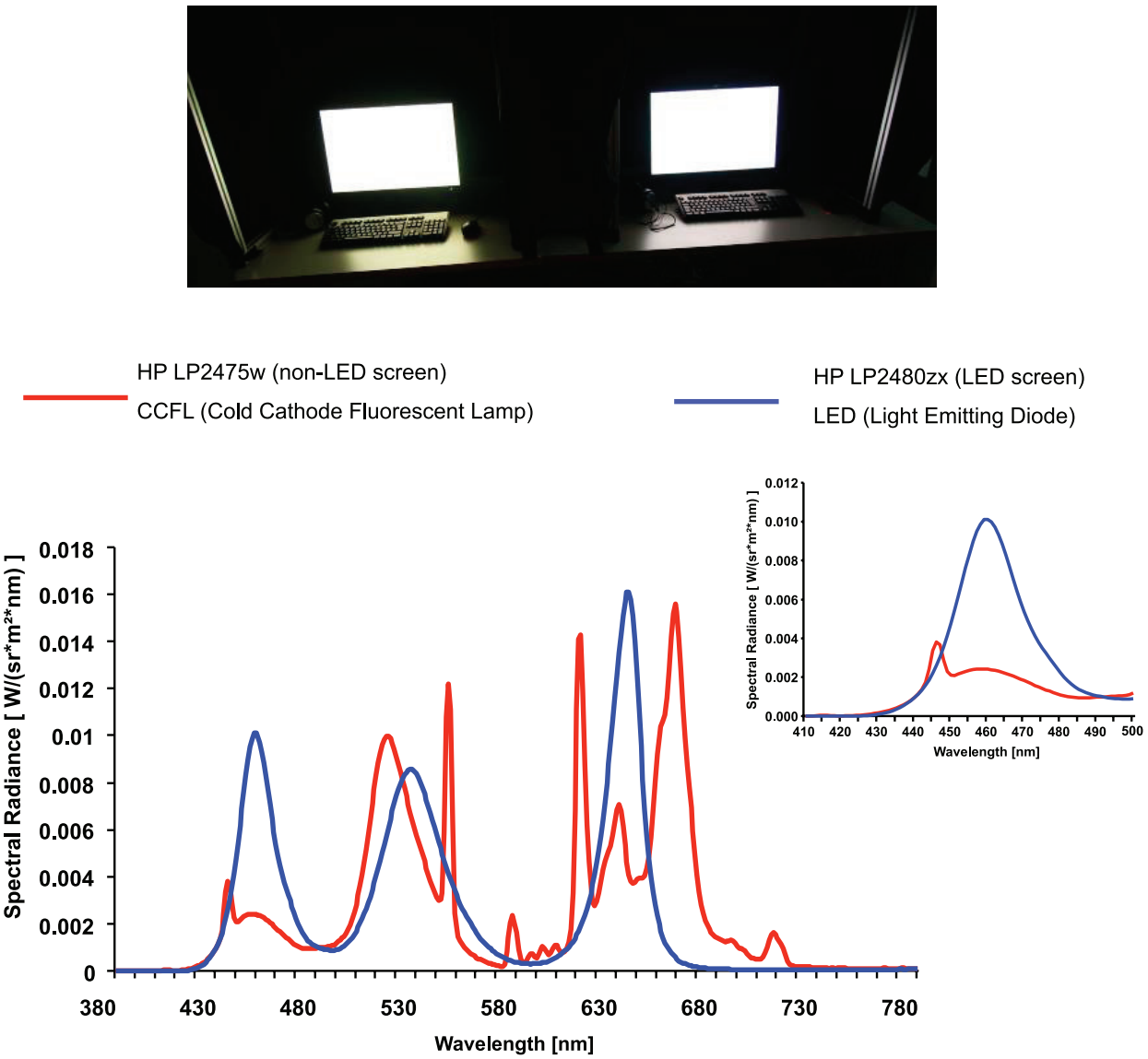


Fig. 1. *Top*, *left*: photograph of the non-light-emitting diodes (non-LED) computer screen [HP LP2475w cold cathode fluorescent lamp (CCFL)]; *right*: photograph of the LED computer screen (HP LP2480zx LED). *Lower*: spectral composition {light wavelength by irradiance = Watt/(steradian × $m^2$ × nm) [W/(sr × $m^2$ × nm)]} of light emitted from the LED computer screen (blue line) and the non-LED screen (red line). *Inset*: blow-up of the spectral composition in the wavelength range of 410–500 nm. The photon flux for the LED-backlit screen was 2.1 × $10^{13}$ photons/($cm^2$ × s) in the wavelength range of 454 and 474 nm and 0.7 × $10^{13}$ photons/($cm^2$ × s) in the wavelength range of 454 and 474 nm for the non-LED-backlit screen.

in color temperature was visible, the study volunteers did not notice this difference after 1 wk when they changed to the other computer screen, because the two displays were arranged in such a way that the participants could only view one (their "own") monitor at a time. During the entire study protocol, the study volunteers were in a seated position in front of the computer screen with an ambient temperature of 22°C, air humidity of 60%, and ambient lighting conditions <4 lux. The volunteers reported 6 h (on average, at ~17.30 h) prior to usual bed time, which was on average, 23.35 h ± 22 min, to the Chronobiology Laboratory of the Psychiatric Hospitals of the University of Basel, where they were equipped with electrodes and sensors for the physiological recordings. Afterward, volunteers were trained on the different cognitive tasks and were acquainted with the study room. Four and one-half hours prior to usual bed time (on average, at 19:00 h), volunteers were dark adapted for 30 min and thus sat in a very dim-light (<4 lux, red light) environment. After dark adaptation (on average, at ~20:00 h), they were asked to sit in front of their computer screen in their cubicles and to start the 5-h screen exposure episode. During these 5 h, the study participants were asked to complete the following tasks: in half-hourly intervals, saliva collection and the Karolinska Sleepiness Scale (12); and in hourly intervals, the Karolinska Drowsiness Test (KDT) (1). Every hour before and after the relaxing movie (see below in this paragraph), the GO/NOGO task (3), time estimation task (30), word-pair learning task (26), and visual comfort and effort scale (4) were completed. Every 50 min, the volunteers were asked to take a short break for 10 min under dim-light red conditions in the same room. Furthermore, after the first 2 h of sitting in the cubicle, a relaxing, 20-min movie was displayed on the computer screen, which contained scenes with snowy environments (i.e., white light). The volunteers were instructed to watch the movie at a distance of ~1 m to ensure constant exposure to the computer screen light without other ongoing activities (which accentuates light's effects on alertness and attention). One hour after the usual bed time (on average, at 00:30 h), the 5-h laboratory protocol ended, and the volunteers were allowed to go home. One week later, the entire study procedure was repeated with the other computer screen type. The order of the computer screens was balanced and crossed over to avoid potential sequence effects.

Saliva collections were scheduled every 30 min. 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) (32). The minimum detectable dose of melatonin (analytical sensitivity) was determined to be 0.2 pg/ml.

To objectively quantify sleepiness, 3-min KDT (1) artifact-free EEG samples were recorded, once during dim light and hourly during the 5 h of light exposure. The Visual Comfort Scale (4), a 100-mm visual analogue scale, comprises: *1*) screen quality (to read, see patterns, and optical reflection); *2*) visual well-being and comfort; and *3*) glare and brightness. Glare and brightness are probed as, respectively, "Does the light have less glare or more?" and "Is the light too dark or too bright?" More glare and brightness are conceived as helping to visualize patterns and/or to read, although high levels of glare and brightness can point to potentially less comfortable light perception in a given environmental light setting (9).

The GO/NOGO task (3) was used to measure the capacity for sustained attention and response control. Participants had to press the space bar within 0.5 s if the letter "M" were shown on the screen. If the letter "W" were shown, participants were instructed not to press any buttons. A total of 80% of M letters were shown in a quasi-random sequence. Approximately 200 M letters were shown during 8 min.

Interval timing was sampled via the concurrent use of two standard methods of timing research, temporal production, and temporal reproduction. For duration estimations, production target durations were displayed in conventional units (number of seconds to be produced) centrally on a computer display using black Arabic digits on a gray background. The participant's task was to identify the target duration and immediately begin holding down the space bar on the computer keyboard, stopping to depress the space bar after a duration that subjectively matched the defined target duration. Reproduction target durations were given via a "carrier stimulus," i.e., via temporally delimited display of a black square on gray background centrally on a computer display. Participants were instructed to hold down the space bar on the computer keyboard as soon as possible upon the extinction of the target stimulus and to release the space bar after a duration, subjectively corresponding to the target duration, had elapsed. Interval timing sessions consisted of either 15 (production; three target durations, each presented five times in random order) or 25 (reproduction; five target durations, each presented five times in random order) (30).

Declarative memory performance was tested via a word-pair learning task, which consisted of 60 word pairs of semantically unrelated words. For each of the four test sessions, a new set of 120 words or 60 word pairs, respectively, was used. To allow the creation of multiple word-pair lists with different words but similar psycholinguistic properties, the software EQUIWORD (16) was used. Each pair of words was displayed on the screen for 6 s, followed by a white-centered fixation cross for 5 s, during which subjects were instructed to visually imagine a relationship between the two words of the pair in the aim to render mnemonic strategies more comparable across volunteers (11, 26). Immediately after the end of the encoding session, the recall of the word pairs was conducted. Thereby, 50% of the previously learned word pairs (=30 word pairs) were shown again, although in a different order, and the remaining 60 words were newly arranged to 30 word pairs. Hence, similar to the encoding session, the recall session comprised 60 word pairs, but 30 of them were newly arranged. For each word pair, the volunteers were asked to answer in the following manner: *1*) it was a known (old) word pair (100% sure), *2*) it was never displayed before (new; 100% sure), or *3*) it is likely but not 100% sure to be a known (old) word pair. The assessment of declarative memory performance was based on the percentage of correctly remembered "old" word pairs and correctly identified "new" word pairs.

EEGs were calculated offline from a continuous, 6-referential EEG recording. All signals were online digitized (16 bit analog-to-digital converter, 0.021 μV/bit; storage sampling rate at 512 Hz Varioport digital recorder, Becker Meditec, Karlsruhe Germany). The raw signals were stored online on a memory card (SanDisk, Milpitas, CA) and downloaded offline to a personal computer hard drive. EEG data collected during the 3-min KDT were scored for artifacts and subjected to a Fast Fourier Transform (FFT) routine (Vitaport paperless sleep-scoring software). Two-second epochs were offline subjected to spectral analysis using a FFT (10% cosine window), resulting in a 0.5-Hz bin resolution. For data reduction, artifact-free, 2-s epochs were averaged over 20-s epochs. Next, the 20-s epochs were further reduced by averaging them over each 3-min KDT. EEG power spectra during each 3-min KDT were calculated for the derivations Fz, FCz, Cz, CPz, Pz, and Oz in the range of 0.5 to 25 Hz. The electrodes for the electrooculogram (EOG) were placed at the outer canthi of each eye, one slightly above the canthomeatal plane and the other slightly below. All EOG recordings were inspected visually, and slow eye movements (SEMs) were scored in 20-s epochs. Other eye movements (i.e., saccadic and mixed patterns) were not considered for analysis. Each 20-s epoch during the study protocol was scored as to whether at least one SEM occurred, and the presence of more than one SEM in an epoch did not influence the scoring criteria. SEMs were scored regardless of their amplitude, but SEMs that occurred during body movements were not included in the analysis.

For all analyses, the statistical package SAS (Version 9.1, SAS Institute, Cary, NC) was used. Statistical analyses were carried out for each variable (subjective sleepiness, GO/NOGO, declarative memory, time estimation, wake-EEG activity, and salivary melatonin) with a repeated measure ANOVA (rANOVA) using a general linear model.

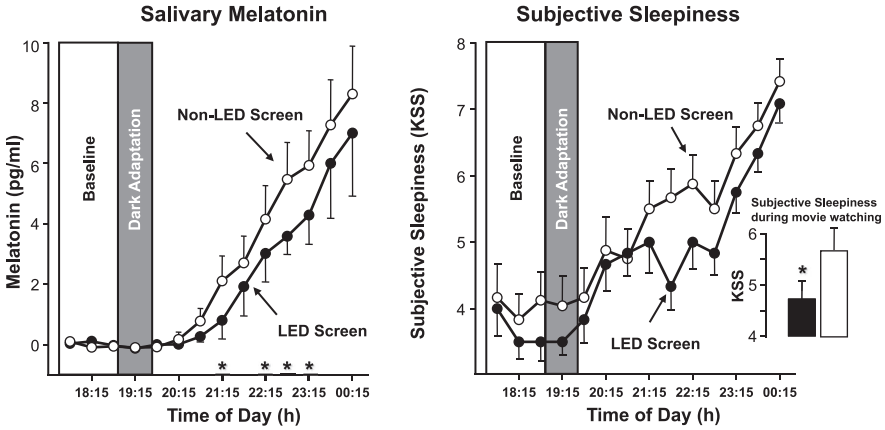


Fig. 2. Time course of salivary melatonin (*left*) and subjective sleepiness levels (*right*) during baseline, dark adaptation, and the screen exposure episode (30 min; mean values ± SE; $n = 13$). *Inset*, *right*: Karolinska Sleepiness Scale (KSS) levels during the presentation of the movie from 21:45–22:15 h. Results of the LED computer screen condition (●); data of the non-LED computer screen condition (○). *Significant post hoc comparisons when the interaction screen × time of day yielded significance.

Factors in this model included "screen type" (LED vs. non-LED-backlit computer screen), "time of day," and for the wake-EEG activity, it included factor "derivation" (frontal, central, parietal, and occipital derivations).

*P* values were based on corrected degrees of freedom, but the original degrees of freedom are reported. Post hoc comparisons were performed using two-sided Duncan's multiple range tests or paired *t*-tests. Since salivary melatonin and subjective sleepiness were also collected during baseline and dark adaptation, these data were included in the analyses. For all of the cognitive tasks, data from the 5-h computer light exposure were included in the analysis. For the analysis of visual comfort, the five time points when it was carried out were averaged to provide a global comparison between the two light settings.

## RESULTS

Salivary melatonin levels followed during baseline, dark adaptation, and a 5-h screen exposure episode yielded a significant effect for screen ($F_{1,11} = 5.9$; $P = 0.045$), time of day ($F_{12,132} = 137.5$; $P < 0.0001$), and the interaction screen versus time of day ($F_{12,132} = 3.0$; $P = 0.041$; Fig. 2, *left*). The evening increase in endogenous melatonin levels was suppressed and rose later under exposure to the LED screen compared with the non-LED screen, significant at the following time points: 21:15 h, 22:15 h, 22:45 h, and 23:15 h (post hoc comparisons; $P$ at least $<0.04$). Subjective sleepiness ratings taken at the same time intervals as for the salivary melatonin assessments yielded a significant effect of time of day ($F_{12,132} = 25.9$; $P < 0.0001$; Fig. 2, *right*) but no significant effect for screen or for the interaction screen versus time of day. However, a separate analysis of subjective sleepiness confined to the period when the participants were asked to take a break and watch the movie (see METHODS) revealed significantly lower sleepiness levels when the movie was displayed on the LED screen compared with the non-LED screen (Fig. 2, *inset*, *right*, $P < 0.04$). Analysis of the incidence of SEMs, an objective marker for sleepiness derived from the EOGs, revealed significant differences for main factors "screen" and "night," although the interaction was not significant (screen: $F_{1,11} = 26.2$; $P < 0.0004$; time of day: $F_{11,44} = 7.8$; $P < 0.0001$; screen vs. time of day: not significant; Fig. 3, *left*). A two-way rANOVA for spectral EEG power density during the KDTs revealed a significant interaction between the factors screen and EEG derivation in the frequency bins ranging from 1 to 7 Hz (*P* at least 0.05). Thus EEG power density in these frequency bins were collapsed into a frequency band of 1–7 Hz and further analyzed with a three-way rANOVA, which yielded a significant factor for screen ($F_{1,20} = 6.7$; $P < 0.02$) and derivation ($F_{5,50} = 124.2$; $P < 0.0001$), a significant interaction screen versus EEG derivation ($F_{5,50} = 2.6$; $P < 0.05$), and a significant interaction EEG derivation versus time of day ($F_{20,200} = 2.9$; $P < 0.02$). Accordingly, exposure to the LED screen resulted in an attenuation of frontal EEG activity in the range 1–7 Hz (Fig. 3, *right*), which was not observed in other derivations.

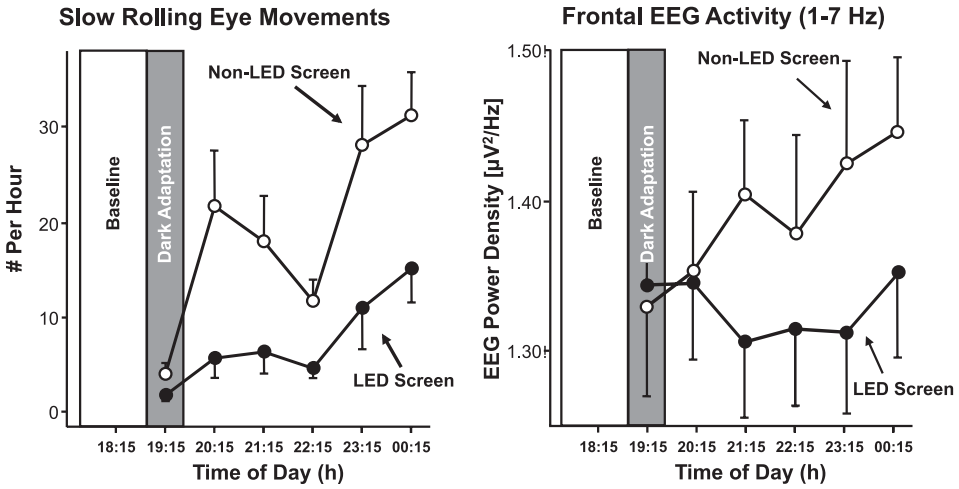


Fig. 3. Time course of the incidence of slow rolling eye movements derived from the electrooculogram (*left*) and frontal low-frequency EEG activity in the range of 1–7 Hz (*right*) during dark adaptation and the screen exposure episode (20:00–00:15 h; mean values ± SE; $n = 13$). Results of the LED computer screen condition (●); data of the non-LED computer screen condition (○).

Similarly, sustained attention (as indexed by reaction times in the GO/NOGO performance) was significantly improved in the LED screen compared with the non-LED screen condition, as indicated by a significant effect of screen ($F_{1,11} = 12.2$; $P < 0.04$), time of day ($F_{11,44} = 7.8$; $P < 0.02$), and the interaction term screen versus time ($F_{12,132} = 3.0$; $P = 0.041$; post hoc comparisons at 22:15 h and 23:15 h: $P < 0.04$; Fig. 4, *left*). The time course of the participant's performance in the time reproduction task for the 10-s interval is illustrated in Fig. 4, *middle*. A significant factor screen ($F_{1,11} = 5.8$; $P < 0.04$), time interval (5, 10, 15 s; $F_{2,22} = 81.4$; $P < 0.0001$), and the interaction screen versus time of day ($F_{3,33} = 3.7$; $P < 0.03$) were elicited. Post hoc testing revealed a significantly faster reproduction (i.e., a more pronounced underestimation of reproducible time intervals) under the LED screen condition at 21:30 h ($P < 0.04$). Similar results as for time reproduction were found for time production (data not shown). In the learning task, the percentage of correctly recognized old word pairs did not significantly differ between the LED and the non-LED screen (data not shown). Interestingly, volunteers identified more newly introduced word pairs during the recall session under the LED screen condition compared with the non-LED screen condition, as indicated by a significant interaction screen versus time of day ($F_{3,30} = 3.6$; $P < 0.03$), with a significant post hoc comparison at 21:30 h ($P < 0.02$; Fig. 4, *right*).

Finally, subjective ratings of screen quality and visual comfort did not reveal any differences between the two screens, whereas the non-LED screen tended to be considered to provide more glare and brightness ($P < 0.1$; see Supplemental figure).

## DISCUSSION

Evening exposure to a LED-backlit computer screen resulted in attenuated salivary melatonin and sleepiness levels with a concomitant increase in cognitive performance associated with sustained attention and with working and declarative memory. Given that the measured illuminance levels and the subjective ratings of visual comfort of both LED and non-LED screens were very similar, we assume that the disparity of the light's spectral composition emitted by the LEDs was the major factor contributing to the observed effects. Indeed, the LED-backlit screen emitted 3.32 times more light in the blue range between 440 and 470 nm than the non-LED-backlit screen. Our data correspond with previous observations that human circadian physiology and alertness levels are particularly sensitive to short-wavelength light (5, 6, 8, 9, 17, 18, 24, 28, 31). New in the current findings is that this effect occurs with nonmonochromatic light sources at relatively low light levels and that it impinges on sustained attention and performance during higher cognitive tasks involving working and declarative memory systems. Whether the observed faster estimation of time and the better recognition of new, interspersed word-pair items during the recall session are related to the enhanced alertness levels or represent an effect on brain structures involved in memory per se need to be further explored by functional imaging data. In any event, we could not find a significant correlation between alertness and memory performance levels, which rather points to a weak association between these two measures. Recent functional MRI experiments have shown that light independently affects alertness-related subcortical structures in the brain stem as well as higher-order cortical areas, including the fronto-polar, lateral prefrontal cortex, premotor cortex, intraparietal sulcus, insula, cerebellum, and thalamus, all of which are known to be involved in executive control and working memory (29). Interestingly, many of these brain structures play an important role in "duration estimation" or explicit timing in the supra-second range (10), as well as in performance requiring more long-term memory stores for declarative learning (21, 33). We may speculate that blue-enriched light emitted by the LED-backlit screen had beneficial effects on working memory demands, as indexed by a faster production and reproduction of time intervals in the supra-second range (5–15 s), as well as on declarative memory, as indexed by a better recognition of newly acquired word pairs. Thus our effects point to a superiority of the LED-backlight screen in terms of enhancing alertness and cognitive performance in the evening.

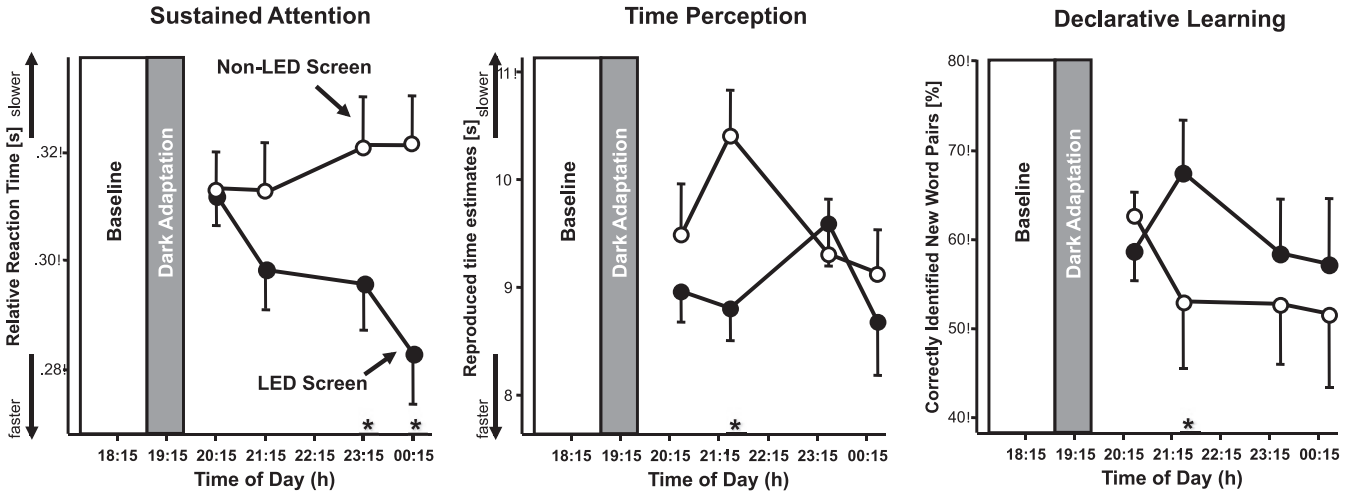


Fig. 4. Time course of cognitive performance during the screen exposure episode: sustained attention, as assessed by the GO/NOGO paradigm; working memory/attention, as assessed by a time perception task; and declarative memory, as assessed by a word-pair learning task (mean values ± SE; $n = 13$). Results of the LED computer screen condition (●); data of the non-LED computer screen condition (○). *Significant post hoc comparisons when the interaction screen × time of day yielded significance.

Since the endogenous evening rise in melatonin occurred later in the LED-backlight condition, the circadian pacemaker located in the suprachiasmatic nuclei most likely received a longer "day" signal, which could have induced a phase delay. Although, we did not assess the circadian phase shift the day after light exposure, this shift would be predicted to be moderate (ca. 30 min).

However, any delay in the melatonin rise has consequences for the parallel rise in sleep propensity. The increased alertness is useful for working but late at night, not for falling asleep. Thus the findings are double edged. The exposure duration used in our study (i.e., a single session of 5 h) was rather modest. When one considers a recent national survey in the United States, 8- to 18-year-olds devote today an average of 7 h and 38 min to using entertainment media across a typical day [more than 53 h/wk (25)]. Children and adolescents spend their leisure time in front of gaming consoles, televisions, and cell phones, and in fact, many adolescents do "multi-screening," which means that they use more than one screen at a time. If one assumes that they spend part of this time in front of a computer screen, particularly during the evening, this behavior and our results here could contribute to answering the question of why an increasing number of sleep problems, particularly delayed sleep phase, are reported for this age group (22). Indeed, we could recently show that evening exposure to monochromatic light at 464 nm can significantly reduce EEG slow-wave activity (SWA) during non-rapid eye movement (NREM) sleep in the first sleep cycle, which was compensated by an intra-night rebound of SWA in the last NREM sleep episode (20).

If one evening can result in later sleep times, as might be predicted from our data, then continued daily computer use may delay sleep times more often. Whether computer screens contribute to a late chronotype requires further investigation (13, 15). Indeed, although the chronic use of LED screens immediately prior to sleep may result in circadian phase shifts and alterations in sleep, we have insufficient studies that have looked at these long-term effects. Thus possible detrimental effects of LED screens are as yet unclear. Our data suggest that rather short exposures (5 h) at low-light intensities (<100 lux, at a distance of 50 cm) with a relative high amount of short-wavelength LED light can evoke circadian melatonin responses and behavioral changes, as measured in alertness levels and cognitive performance. However, this should be viewed with caution, since the spectral profiles of the two screens varied in ways other than just short-wavelength emission. Another study limitation is the fact that this study was conducted only on men. This was mainly due to the fact that menstrual phase and use of oral contraceptives could alter, for instance, melatonin secretion [for a review, see ref. (2)]. Future studies are needed to investigate these effects in women. Furthermore, technical progress is needed to build LED devices, which may adapt their emitted light spectrum dynamically according to the time of day, such as the f.lux program (stereopsis.com), and even better, to the user's sleep-wake timing. Ideally, computer screens would therefore not only be an interface for electronic information exchange but also help to provide essential light information to the circadian timing system by positively supporting circadian alignment with individually timed backlight changes of the spectral profile of the computer screen.

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## DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

## REFERENCES

1. **Åkerstedt T, Gillberg M.** Subjective and objective sleepiness in the active individual. *Int J Neurosci* 52: 29–37, 1990.
2. **Baker FC, Driver HS.** Circadian rhythms, sleep, and the menstrual cycle. *Sleep Med* 8: 613–622, 2007.
3. **Barry RJ, de Pascalis V, Hodder D, Clarke AR, Johnstone SJ.** Preferred EEG brain states at stimulus onset in a fixed interstimulus interval auditory oddball task, and their effects on ERP components. *Int J Psychophysiol* 47: 187–198, 2003.
4. **Boyce PR.** Lighting research for interiors: the beginning of the end or the end of the beginning. *Lighting Res Technol* 36: 283–294, 2004.
5. **Brainard G, Hanifin JP, Rollag MD, Greeson J, Byrne B, Glickman G, Gerner E, Sanford B.** Human melatonin regulation is not mediated by the three cone photopic visual system. *J Clin Endocrinol Metab* 86: 433–436, 2001.
6. **Brainard GC, Hanifin JP, Greeson JM, Byrne B, Glickman G, Gerner E, Rollag MD.** Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *J Neurosci* 21: 6405–6412, 2001.
7. **Cajochen C, Dijk DJ, Borbély AA.** Dynamics of EEG slow-wave activity and core body temperature in human sleep after exposure to bright light. *Sleep* 15: 337–343, 1992.
8. **Cajochen C, Münch M, Kobialka S, Kräuchi K, Steiner R, Oelhafen P, Orgül S, Wirz-Justice A.** High sensitivity of human melatonin, alertness, thermoregulation and heart rate to short wavelength light. *J Clin Endocrinol Metab* 90: 1311–1316, 2005.
9. **Chellappa SL, Steiner R, Blattner P, Oelhafen P, Götz T, Cajochen C.** Non-visual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? *PLos One* 6: 2011.
10. **Coull JT, Cheng RK, Meck WH.** Neuroanatomical and neurochemical substrates of timing. *Neuropsychopharmacology* 36: 3–25, 2011.
11. **Gais S, Mölle M, Helms K, Born J.** Learning-dependent increases in sleep spindle density. *J Neurosci* 22: 6830–6834, 2002.
12. **Gillberg M, Kecklund G, Åkerstedt T.** Relations between performance and subjective ratings of sleepiness during a night awake. *Sleep* 17: 236–241, 1994.
13. **Higuchi S, Motohashi Y, Liu Y, Ahara M, Kaneko Y.** Effects of VDT tasks with a bright display at night on melatonin, core temperature, heart rate, and sleepiness. *J Appl Physiol* 94: 1773–1776, 2003.
14. **Khalsa SBS, Jewett ME, Cajochen C, Czeisler CA.** A phase response curve to single bright light pulses in human subjects. *J Physiol* 549: 945–952, 2003.
15. **Kohyama J.** A newly proposed disease condition produced by light exposure during night: asynchronization. *Brain Dev* 31: 255–273, 2009.
16. **Lahl O, Pietrowsky R.** EQUIWORD: a software application for the automatic creation of truly equivalent word lists. *Behav Res Methods* 38: 146–152, 2006.
17. **Lockley SW, Brainard GC, Czeisler CA.** High sensitivity of the human circadian melatonin rhythm to resetting by short wavelength light. *J Clin Endocrinol Metab* 88: 4502–4505, 2003.
18. **Lockley SW, Evans EE, Scheer FA, Brainard GC, Czeisler CA, Aeschbach D.** Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. *Sleep* 29: 161–168, 2006.
19. **Monteleone P, Martiadis V, Maj M.** Circadian rhythms and treatment implications in depression. *Prog Neuropsychopharmacol Biol Psychiatry;* doi: 10.1016/j.physletb.2003.10.071.
20. **Münch M, Kobialka S, Steiner R, Oelhafen P, Wirz-Justice A, Cajochen C.** Wavelength-dependent effects of evening light exposure on sleep architecture and sleep EEG power density in men. *Am J Physiol Regul Integr Comp Physiol* 290: R1421–R1428, 2006.

21. **Poldrack RA, Gabrieli JD.** Functional anatomy of long-term memory. *J Clin Neurophysiol* 14: 294–310, 1997.
22. **Reid GJ, Huntley ED, Lewin DS.** Insomnias of childhood and adolescence. *Child Adolesc Psychiatr Clin N Am* 18: 979–1000, 2009.
23. **Reid KJ, Zee PC.** Circadian rhythm sleep disorders. *Handb Clin Neurol* 99: 963–977, 2011.
24. **Revell VL, Arendt J, Fogg LF, Skene DJ.** Alerting effects of light are sensitive to very short wavelengths. *Neurosci Lett* 399: 96–100, 2006.
25. **Rideout VJ, Foehr UG, Donald FR.** *Generation M2: Media in the Lives of 8- to 18-Year-Olds*. Menlo Park, CA: Kaiser Family Foundation, 2010, p. 1–79.
26. **Schmidt C, Peigneux P, Muto V, Schenkel M, Knoblauch V, Münch M, De Quervain DJF, Wirz-Justice A, Cajochen C.** Encoding difficulty promotes postlearning changes in sleep spindle activity during napping. *J Neurosci* 26: 8976–8982, 2006.
27. **Schwartz JR, Roth T.** Shift work sleep disorder: burden of illness and approaches to management. *Drugs* 66: 2357–2370, 2006.
28. **Thapan K, Arendt J, Skene DJ.** An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. *J Physiol* 535: 261–267, 2001.
29. **Vandewalle G, Maquet P, Dijk DJ.** Light as a modulator of cognitive brain function. *Trends Cogn Sci* 13: 429–438, 2009.
30. **Wackermann J, Spati J.** Asymmetry of the discrimination function for temporal durations in human subjects. *Acta Neurobiol Exp (Wars)* 66: 245–254, 2006.
31. **Warman VL, Dijk DJ, Warman GR, Arendt J, Skene DJ.** Phase advancing human circadian rhythms with short wavelength light. *Neurosci Lett* 342: 37–40, 2003.
32. **Weber JM, Schwander JC, Unger I, Meier D.** A direct ultrasensitive RIA for the determination of melatonin in human saliva: comparison with serum levels. *J Sleep Res* 26: 757, 1997.
33. **Winocur G, Moscovitch M, Bontempi B.** Memory formation and long-term retention in humans and animals: convergence towards a transformation account of hippocampal-neocortical interactions. *Neuropsychologia* 48: 2339–2356, 2010.
34. **Zavada A, Gordijn MC, Beersma DG, Daan S, Roenneberg T.** Comparison of the Munich Chronotype Questionnaire with the Horne-Ostberg's Morningness-Eveningness Score. *Chronobiol Int* 22: 267–278, 2005.