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

Christian Cajochen¹, Sylvia Frey¹, Doreen Anders¹, Jakub Spätì¹, Matthias Bues², Achim Pross², Ralph Mager³, Anna Wirz-Justice¹, Oliver Stefani²

¹ Centre for Chronobiology, Psychiatric Hospitals of the University of Basel, Wilhelm Kleinstr. 27, 4012 Basel, Switzerland
² Competence Team Visual Technologies, Fraunhofer IAO/University Stuttgart IAT Nobelstr. 12, 70569 Stuttgart, Germany
³ Center for Applied Technologies in Neuroscience-Basel, Psychiatric Hospitals of the University of Basel, Wilhelm Kleinstr. 27, 4012 Basel, Switzerland

Running Title: Computer screen and circadian and cognitive physiology

Corresponding author:
Christian Cajochen, PhD
Centre for Chronobiology
Psychiatric Hospital of the University of Basel,
Wilhelm Kleinstr. 27
CH-4012 Basel, Switzerland
Tel.: +41613255318
Fax: +41613255556
Email: christian.cajochen@upkbs.ch
Web: www.chronobiology.ch
Abstract (250 words)

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 cross-over 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 W/(sr*m²), $2.1 \times 10^{13}$ photons/(cm²*s) in the wavelength range of 454 and 474 nm] than a white non-LED backlit screen [irradiance of 0.099 W/(sr*m²), $0.7 \times 10^{13}$ photons/(cm²*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 electroencephalographic 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 to 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 whose spectral profile can be individually programmed to add timed, essential light information to the circadian system in humans.

Keywords (3-5): Non-visual effects of light, spectral analysis, shift work, melatonin, alertness
Introduction

The world is online. Over 2 billion people use the internet and this number is rapidly increasing. In 2010, 1.6 billion computers, TV 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, etc. Newer computers and TV screens are now frequently equipped with light emitting diodes (LED) that peak in the short wavelength region (i.e. the blue range at around 460 nm). There is ample evidence that a novel short-wavelength-sensitive photoreceptor system is primarily responsible for a variety of non-visual 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 electroencephalogram (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 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 upon the circadian phase of light exposure. Phase delays occur when light exposure is centered prior to the core body temperature minimum, while 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. 460nm) in comparison to 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 to 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 to 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 their sleep-wake
behavior [Munich Chronotype questionnaire, MCTQ (34)]. Volunteers with good sleep
quality (PSQI score<5), no extreme chronotype (>3 and <6 points on 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 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 months, and transmeridian flights up to 3 months prior to 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 two weeks, participants were instructed to keep a regular sleep-wake schedule (bedtimes 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 Ltd, 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 square meter 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 about 60 cm. Two different computer screens were compared, a LED-illuminated LCD screen (HP LP2480zx) and a CCFL-illuminated screen (HP LP2475w), both with a screen diagonal of 24 inches and a resolution of 1920x1200 pixels adjusted to the identical luminance of 250 nits (nits as 1 cd/m2). Spectral measurements were carried out using a Konica Minolta CS-1000 (Konica Minolta Sensing, Inc., Osaka, Japan). Both computer screens were set to a white background with a color temperature of 6953 K for the LED-illuminated and 4775K for the CCFL-illuminated screen, thus reducing the amount of blue light from half to approximately one third in the LED compared to the non-LED CCFL illuminated screen. The irradiance between 400nm and 480nm of the LED illuminated computer screen was 0,241 W/(sr*m²) and 0,099 W/(sr*m²) for the non-LED CCFL illuminated computer screen (Figure 1). Although the difference in color temperature was visible, the study volunteers did not notice this difference after one week when they changed to the other computer screen, because the two displays were arranged 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 hours (on average around 17.30h) prior to usual bedtime, which was on average 23.35h ± 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. Afterwards, volunteers were trained on the different cognitive tasks and were acquainted with the study room. Four and a half hours prior to usual bedtime (on average at 19:00h), volunteers were dark adapted for 30 minutes and thus sat in a very dim light (<4 lux, red light) environment. After dark adaptation (on average at around 20:00h), 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 hours the study participants were asked to complete the following tasks: in half-hourly intervals saliva collection and the Karolinska Sleepiness Scale [KSS; (12)] and in hourly intervals the Karolinska Drowsiness Test [KDT; (1)]. Every hour before and after the relaxing movie (see below) the GO/NO-GO task (3), the time estimation task (30), the word pair learning task (26) and the visual comfort and effort scale (4) were completed. Every 50 minutes, the volunteers were asked to take a short break for 10 minutes under dim light red conditions in the same room. Furthermore, after the first two hours 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 approximately 1 meter to ensure constant exposure to the computer screen light without on-going other activities (which accentuates light’s effects on alertness and attention). One hour after usual bedtime (on average 00:30h) 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 minutes. A direct double-antibody radioimmunoassay was utilized for the melatonin assay (validated by gas chromatography–mass spectroscopy 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 5h of light exposure. The Visual Comfort Scale (4), a 100mm 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 second if the letter “M” was shown on the screen. If the letter “W” was 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”s were shown during 8 minutes.

Interval timing was sampled via the concurrent use of two standard methods of timing research, temporal production and temporal re-production. 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 grey back-ground.

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 grey 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; 3 target durations, each presented 5 times in random order) or 25
(reproduction; 5 target durations, each presented 5 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 4 test sessions a new set of
120 words or 60 word pairs respectively was used. In order 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 immediate recall of the word pairs was conducted. Thereby, 50% of the
previously learned word pairs (= 30 word pairs) were shown again – though in different
order - and the remaining 60 words were newly arranged to 30 word pairs. Hence, as 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:
a) it was a known (old) word pair (100% sure), b) it was never displayed before (=new; 100% sure), or c) 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 off-line from a continuous 6-referential EEG recording. All signals were on-line digitized (16 bit AD converter, 0.021 μV/bit; storage sampling rate at 512 Hz Varioport digital recorder, Becker Meditec, Karlsruhe Germany). The raw signals were stored on-line on a memory card (SanDisk, USA) and downloaded off-line to a PC hard drive. EEG data collected during the 3-min KDT were scored for artifacts and subjected to a fast Fourier transform routine (Vitaport paperless sleep scoring software). Two-second epochs were off-line subjected to spectral analysis using a fast Fourier transform (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 0.5-25 Hz. The electrodes for the electrooculogram (EOG) were placed at the outer canthi of each eye, one slightly above the cantomeatal plane, 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 or not 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 (SAS Institute Inc., Cary, NC, USA; Version 6.12) was utilized. 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 analysis of variance (rANOVAs) using a general linear model (PROC GLM). 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 the cognitive tasks, data from the 5-hour computer light exposure was 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 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 vs. time of day (*F*$_{12,132}$=3.0; *p*=0.041, Figure 2, left panel). The evening increase in endogenous melatonin levels was suppressed and rose later under exposure to the LED screen compared to the non-LED screen, significant at the following time points: 21:15h, 22:15h, 22:45h and 23:15h (*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,
Figure 2, right panel), but no significant effect for screen nor for the interaction screen vs. 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 to the non-LED screen (inset Figure 2, right panel, \( p < 0.04 \)). Analysis of the incidence of SEMs, an objective marker for sleepiness derived from the electrooculograms, 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, Figure 3, left panel). A 2-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 3-way rANOVA, which yielded a significant factor for screen (\( F_{1,20} = 6.7; p < 0.02 \), derivation (\( F_{5,50} = 124.2; p < 0.0001 \)), a significant interaction screen vs. EEG-derivation (\( F_{5,50} = 2.6; p < 0.05 \)) and a significant interaction EEG-derivation vs. 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 from 1-7 Hz (Figure 3, right panel), which was not observed in other derivations.

Similarly, sustained attention (as indexed by reaction times in the GO/NOGO performance) was significantly improved in the LED screen as compared to 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 vs. time \( F_{12,132} = 3.0; p = 0.041 \); post-hoc comparisons at 22:15h and 23:15h: \( p < 0.04 \), Figure 4, left panel). The time course of the participant’s performance in the time reproduction task for the 10-s interval is illustrated in Figure 4,
middle panel. A significant factor screen ($F_{1,11} = 5.8; p<0.04$), time interval $(5, 10, 15\text{s}; F_{2,22} = 81.4; p<0.0001$), and the interaction screen vs. time of day $(F_{3,33} = 3.7; p<0.03$) was 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 21:30h ($p<0.04$). 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 as compared with the non-LED screen condition, as indicated by a significant interaction screen vs. time of day $(F_{3,30} = 3.6; p<0.03$), with a significant post-hoc comparison at 21:30h ($p<0.02$, Figure 4 (right panel). 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 ($p<0.1$, 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 current findings is that this effect occurs with non-monochromatic 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 is related to the enhanced alertness levels or represent an effect on brain structures involved in memory per se, needs 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 fMRI experiments have shown that light independently affects alertness-related subcortical structures in the brainstem as well as higher order cortical areas, including the fronto-polar, lateral prefrontal cortex, and premotor cortex, the 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 the 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.
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 minutes).

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 hours) was rather modest. When one considers a recent national survey in the US, 8-18 year-olds devote today an average of 7 hours and 38 minutes to using entertainment media across a typical day [more than 53 hours a week (25)]. Children and adolescents spend their leisure time in front of gaming consoles, televisions, 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 why an increasing number of sleep problems, particularly delayed sleep phase, is reported for this age group (22). Indeed, we could recently show that evening exposure to monochromatic light at 464nm 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 more and more. 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 hours) at low light intensities (<100 lux, at a distance
of 50 cm) with a relative high amount of short-wave length 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 other ways 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 (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.

Acknowledgments

We thank Claudia Renz, Giovanni Balestrieri, Marie-France Dattler and Marielle Kappeler for
their help in data acquisition, Dr. Sarah Chellappa for critical comments on the manuscript
and the volunteers for participating. This study was supported by grants from the Daimler-
Benz-Foundation (CLOCKWORK) and by the EU 6th Framework Project EUCLOCK (#018741).
References


Figure legends

Figure 1. Upper panel: left hand side: photograph of the Non-LED computer screen [HP LP2475w, CCFL (Cold Cathode Fluorescent Lamp)], right hand side: photograph of the LED computer screen (HP LP2480zx LED). Lower panel: Spectral composition [light wavelength by irradiance; Watt/(sr x m2x 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 \times 10^{13} photons/(cm^2*s) in the wavelength range of 454 and 474 nm and 0.7 \times 10^{13} photons/(cm^2*s) in the wavelength range of 454 and 474 nm for the non-LED backlit screen.

Figure 2. Time course of salivary melatonin (left panel) and subjective sleepiness levels (right panel) during baseline, dark adaptation and the screen exposure episode (20:00-00:15h). Mean values + or – SEM, n=13). The inset in the right hand panel depicts KSS levels during the presentation of the movie from 21:45-22:15h. Filled black dots represent results of the LED computer screen condition, open dots indicate data of the non-LED computer screen condition. Asterisks indicate significant post-hoc comparisons, when the interaction screen x time of day yielded significance.

Figure 3. Time course of the incidence of slow rolling eye movements derived from the EOG (left panel) and frontal low frequency EEG activity in the range of 1-7 Hz. (right panel) during dark adaptation and the screen exposure episode (20:00-00:15h). Mean values + or – SEM, n=13). Filled black dots represent results of the LED computer screen condition, open dots indicate data of the non-LED computer screen condition.

Figure 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 + or – SEM, n=13). Filled black dots represent results of the LED computer screen condition, open dots indicate data of the non-LED computer screen condition.

Supplemental figure. Subjective ratings of screen quality, light environment and brightness of the computer screen, as assessed with the visual comfort questionnaire (3) during the LED and the non-LED computer screen condition. Mean values, + SEM, n=13. Solid black bars indicate the LED computer screen condition and open bars the non-LED computer screen condition. The circle indicates a tendency (p=0.1) for the non-LED computer screen to be brighter.
Salivary Melatonin

Subjective Sleepiness

Figure 2
Slow Rolling Eye Movements

Frontal EEG Activity (1-7 Hz)

Figure 3
Visual Comfort Questionnaire

Screen Quality

Light Environment

Brightness

Supplemental Figure