

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

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30 **Running Title:** Computer screen and circadian and cognitive physiology

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47 **Abstract (250 words)**

48 Many people spend an increasing amount of time in front of computer screens equipped
49 with light emitting diodes (LED) with a short-wavelength (blue range). Thus, we investigated
50 the repercussions on melatonin (a marker of the circadian clock), alertness and cognitive
51 performance levels in 13 young male volunteers under controlled laboratory conditions in a
52 balanced cross-over design. A 5-h evening exposure to a white LED backlit screen with more
53 than twice as much 464 nm light emission [irradiance of 0,241 W/(sr*m²), 2.1 x 10¹³
54 photons/(cm²*s) in the wavelength range of 454 and 474 nm] than a white non-LED backlit
55 screen [irradiance of 0,099 W/(sr*m²), 0.7 x 10¹³ photons/(cm²*s) in the wavelength range
56 of 454 and 474 nm] elicited a significant suppression of the evening rise in endogenous
57 melatonin and subjective as well as objective sleepiness as indexed by a reduced incidence
58 of slow eye movements and electroencephalographic low frequency activity (1-7 Hz) in
59 frontal brain regions. Concomitantly, sustained attention as determined by the GO/NOGO
60 task, working memory/attention as assessed by 'explicit timing', and declarative memory
61 performance in a word learning paradigm were significantly enhanced in the LED-backlit
62 screen compared to the non-LED condition. Screen quality and visual comfort were rated the
63 same in both screen conditions, whereas the non-LED screen tended to be considered
64 brighter. Our data indicate that the spectral profile of light emitted by computer screens
65 impacts on circadian physiology, alertness and cognitive performance levels. The challenge
66 will be to design a computer screen whose spectral profile can be individually programmed
67 to add timed, essential light information to the circadian system in humans.

68

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

70

71 **Introduction**

72 The world is online. Over 2 billion people use the internet and this number is rapidly
73 increasing. In 2010, 1.6 billion computers, TV sets and cellular phones were sold globally
74 (www.worldometers.info), which illustrates the numbers of individuals who spend time in
75 front of computer screens, video game consoles, etc. Newer computers and TV screens are
76 now frequently equipped with light emitting diodes (LED) that peak in the short wavelength
77 region (i.e. the blue range at around 460 nm). There is ample evidence that a novel short-
78 wavelength-sensitive photoreceptor system is primarily responsible for a variety of non-
79 visual light responses, in particular resetting the timing of the circadian pacemaker,
80 suppressing melatonin production, improving alertness and performance, and elevating
81 brain activation as assessed from electroencephalogram (EEG)-derived correlates of arousal
82 (5, 6, 8, 17, 18, 24, 28, 31). Furthermore, bright light exposure and exposure to
83 monochromatic blue light in the evening lengthens sleep latency and initial EEG delta
84 activity, a marker of slow wave sleep (7, 20). Thus, the frequent use of LED sources could
85 have ramifications on human behavior, since light is the most important synchronizer of our
86 biological clock. The circadian pacemaker responds differentially to the resetting effects of
87 light, depending upon the circadian phase of light exposure. Phase delays occur when light
88 exposure is centered prior to the core body temperature minimum, while circadian phase
89 advances can be elicited by light exposures centered after the core body temperature
90 minimum, which normally occurs in the second half of the biological night (14). This means
91 that exposure to artificial light in the evening, when our circadian timing system is most
92 vulnerable to light, has the capacity to modify rhythms, and thus sleep and neurobehavioral
93 function. While acute light exposure in the evening may, for instance, help night workers to
94 become more alert and perform better, the repercussions of *chronic* inappropriate timed

95 exposure could lead to circadian misalignment and thus eventually to sleep problems (23),
96 depression (19) and even the cardiovascular diseases seen in shift workers (27).
97 Here we investigated the impact of a LED backlit computer screen (enhanced in the short
98 wavelength region, i.e. 460nm) in comparison to a LED-free computer screen on a wide
99 range of measures in human physiology and behavior, such as melatonin levels, cognitive
100 performance and the EEG during wakefulness. Our main prediction was that a 5-h evening
101 exposure to a LED-backlit computer screen, in comparison to a non-LED computer screen,
102 would suppress the evening increase in melatonin levels and evoke an alerting response,
103 with concomitant improvement in cognitive performance.

104

105 **Methods**

106 Healthy young male volunteers (19 to 35 years) were recruited via advertisements at the
107 University of Basel, Switzerland. Potential study participants filled out questionnaires about
108 their general health, sleep quality (Pittsburgh sleep quality index, PSQI) and their sleep-wake
109 behavior [Munich Chronotype questionnaire, MCTQ (34)]. Volunteers with good sleep
110 quality (PSQI score <5), no extreme chronotype (>3 and <6 points on MCTQ questionnaire),
111 and good general health, underwent a medical examination carried out by the physician in
112 charge and an ophthalmologic examination by a certified optometrist to exclude volunteers
113 with visual impairments, such as color blindness, diminished pupil reaction to light, and a
114 reduced visual field. Participants were not excluded if they wore glasses or contact lenses.
115 Exclusion criteria were smoking, medication or drug consumption, shift work within the last
116 3 months, and transmeridian flights up to 3 months prior to study. Thirteen volunteers
117 (mean age: 23.8 years \pm 5.0 SD, mean Body Mass Index: 22.6 \pm 1.7 SD), were then selected
118 for the study. All subjects gave written informed consent. The study protocol, screening

119 questionnaires and consent form were approved by the local ethics committee and
120 conformed to the Declaration of Helsinki.

121 During the entire study protocol, which comprised a total of two weeks, participants were
122 instructed to keep a regular sleep-wake schedule (bedtimes and wake times within ± 30 min
123 of self-selected target time). Compliance was verified by sleep logs and ambulatory activity
124 measurements (Actiwatch_L®, Cambridge Neurotechnology Ltd, UK). The “in laboratory”
125 part of the study was carried out in Switzerland between the end of September and
126 beginning of November. In a 25 square meter room two cubicles were installed in such a way
127 that they were completely light shielded, and only the light emitted by the computer screen
128 fell onto the volunteers’ eyes at a distance of about 60 cm. Two different computer screens
129 were compared, a LED-illuminated LCD screen (HP LP2480zx) and a CCFL-illuminated screen
130 (HP LP2475w), both with a screen diagonal of 24 inches and a resolution of 1920x1200 pixels
131 adjusted to the identical luminance of 250 nits (nits as 1 cd/m^2). Spectral measurements
132 were carried out using a Konica Minolta CS-1000 (Konica Minolta Sensing, Inc., Osaka,
133 Japan). Both computer screens were set to a white background with a color temperature of
134 6953 K for the LED-illuminated and 4775K for the CCFL-illuminated screen, thus reducing the
135 amount of blue light from half to approximately one third in the LED compared to the non-
136 LED CCFL illuminated screen. The irradiance between 400nm and 480nm of the LED
137 illuminated computer screen was $0,241 \text{ W}/(\text{sr}\cdot\text{m}^2)$ and $0,099 \text{ W}/(\text{sr}\cdot\text{m}^2)$ for the non-LED
138 CCFL illuminated computer screen (Figure 1). Although the difference in color temperature
139 was visible, the study volunteers did not notice this difference after one week when they
140 changed to the other computer screen, because the two displays were arranged such a way
141 that the participants could only view one (their “own”) monitor at a time. During the entire
142 study protocol the study volunteers were in a seated position in front of the computer

143 screen, with an ambient temperature of 22°C, air humidity of 60% and ambient lighting
144 conditions < 4 lux. The volunteers reported 6 hours (on average around 17.30h) prior to
145 usual bedtime, which was on average 23.35h ± 22 min, to the Chronobiology Laboratory of
146 the Psychiatric Hospitals of the University of Basel, where they were equipped with
147 electrodes and sensors for the physiological recordings. Afterwards, volunteers were trained
148 on the different cognitive tasks and were acquainted with the study room. Four and a half
149 hours prior to usual bedtime (on average at 19:00h), volunteers were dark adapted for 30
150 minutes and thus sat in a very dim light (<4 lux, red light) environment. After dark adaptation
151 (on average at around 20:00h), they were asked to sit in front of their computer screen in
152 their cubicles and to start the 5-h screen exposure episode. During these 5 hours the study
153 participants were asked to complete the following tasks: in half-hourly intervals saliva
154 collection and the Karolinska Sleepiness Scale [KSS; (12)] and in hourly intervals the
155 Karolinska Drowsiness Test [KDT; (1)]. Every hour before and after the relaxing movie (see
156 below) the GO/NO-GO task (3), the time estimation task (30), the word pair learning task
157 (26) and the visual comfort and effort scale (4) were completed. Every 50 minutes, the
158 volunteers were asked to take a short break for 10 minutes under dim light red conditions in
159 the same room. Furthermore, after the first two hours sitting in the cubicle a relaxing 20-min
160 movie was displayed on the computer screen, which contained scenes with snowy
161 environments (i.e. white light). The volunteers were instructed to watch the movie at a
162 distance of approximately 1 meter to ensure constant exposure to the computer screen light
163 without on-going other activities (which accentuates light's effects on alertness and
164 attention). One hour after usual bedtime (on average 00:30h) the 5-h laboratory protocol
165 ended, and the volunteers were allowed to go home. One week later, the entire study

166 procedure was repeated with the other computer screen type. The order of the computer
167 screens was balanced and crossed over to avoid potential sequence effects.

168 Saliva collections were scheduled every 30 minutes. A direct double-antibody
169 radioimmunoassay was utilized for the melatonin assay (validated by gas chromatography–
170 mass spectroscopy with an analytical least detectable dose of 0.65 pg/ml; Bühlmann
171 Laboratory, Schönenbuch, Switzerland) (32). The minimum detectable dose of melatonin
172 (analytical sensitivity) was determined to be 0.2 pg/ml.

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

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

186 Interval timing was sampled via the concurrent use of two standard methods of timing
187 research, temporal production and temporal re-production. For duration estimations,
188 production target durations were displayed in conventional units (number of seconds to be

189 produced), centrally on a computer display using black Arabic digits on a grey back-ground.
190 The participant's task was to identify the target duration and immediately begin holding
191 down the space bar on the computer keyboard, stopping to depress the space bar after a
192 duration that subjectively matched the defined target duration. Reproduction target
193 durations were given via a 'carrier stimulus' i.e., via temporally delimited display of a black
194 square on grey background, centrally on a computer display. Participants were instructed to
195 hold down the space bar on the computer keyboard as soon as possible upon the extinction
196 of the target stimulus, and to release the space bar after a duration subjectively
197 corresponding to the target duration had elapsed. Interval timing sessions consisted of
198 either 15 (production; 3 target durations, each presented 5 times in random order) or 25
199 (reproduction; 5 target durations, each presented 5 times in random order) (30).

200 Declarative memory performance was tested via a word pair learning task which consisted of
201 60 word pairs of semantically unrelated words. For each of the 4 test sessions a new set of
202 120 words or 60 word pairs respectively was used. In order to allow the creation of multiple
203 word pair lists with different words but similar psycholinguistic properties the software
204 EQUIWORD (16) was used. Each pair of words was displayed on the screen for 6 s, followed
205 by a white centered fixation cross for 5 s, during which subjects were instructed to visually
206 imagine a relationship between the two words of the pair in the aim to render mnemonic
207 strategies more comparable across volunteers (11, 26). Immediately after the end of the
208 encoding session the immediate recall of the word pairs was conducted. Thereby, 50% of the
209 previously learned word pairs (= 30 word pairs) were shown again – though in different
210 order - and the remaining 60 words were newly arranged to 30 word pairs. Hence, as the
211 encoding session, the recall session comprised 60 word pairs but 30 of them were newly
212 arranged. For each word pair, the volunteers were asked to answer in the following manner:

213 a) it was a known (old) word pair (100% sure), b) it was never displayed before (=new; 100%
214 sure), or c) it is likely but not 100% sure to be a known (old) word pair. The assessment of
215 declarative memory performance was based on the percentage of correctly remembered
216 “old” word pairs and correctly identified “new” word pairs.

217

218 EEGs were calculated off-line from a continuous 6-referential EEG recording. All signals were
219 on-line digitized (16 bit AD converter, 0.021 μ V/bit; storage sampling rate at 512 Hz
220 Varioport digital recorder, Becker Meditec, Karlsruhe Germany). The raw signals were stored
221 on-line on a memory card (SanDisk, USA) and downloaded off-line to a PC hard drive. EEG
222 data collected during the 3-min KDT were scored for artifacts and subjected to a fast Fourier
223 transform routine (VitaPort paperless sleep scoring software). Two-second epochs were off-
224 line subjected to spectral analysis using a fast Fourier transform (FFT, 10% cosine window)
225 resulting in a 0.5-Hz bin resolution. For data reduction, artifact free 2-s epochs were
226 averaged over 20-s epochs. Next, the 20-s epochs were further reduced by averaging them
227 over each 3-min KDT. EEG power spectra during each 3-min KDT were calculated for the
228 derivations Fz, FCz, Cz, CPz, Pz and Oz in the range 0.5 \pm 25 Hz. The electrodes for the
229 electrooculogram (EOG) were placed at the outer canthi of each eye, one slightly above the
230 cantomeatal plane, the other slightly below. All EOG recordings were inspected visually, and
231 slow eye movements (SEMs) were scored in 20-s epochs. Other eye movements (i.e.,
232 saccadic and mixed patterns) were not considered for analysis. Each 20-s epoch during the
233 study protocol was scored as to whether or not at least one SEM occurred, and the presence
234 of more than one SEM in an epoch did not influence the scoring criteria. SEMs were scored
235 regardless of their amplitude, but SEMs that occurred during body movements were not
236 included in the analysis.

237 For all analyses, the statistical package SAS (SAS Institute Inc., Cary, NC, USA; Version 6.12)
238 was utilized. Statistical analyses were carried out for each variable (subjective sleepiness,
239 GO/NOGO, declarative memory, time estimation, wake-EEG activity, and salivary melatonin)
240 with a repeated measure analysis of variance (rANOVAs) using a general linear model (PROC
241 GLM). Factors in this model included “*screen type* (LED vs. non-LED backlit computer screen),
242 “*time of day*”, and for the wake-EEG activity it included factor “*derivation*” (frontal, central,
243 parietal and occipital derivations).
244 *P* values were based on corrected degrees of freedom, but the original degrees of freedom
245 are reported. *Post-hoc* comparisons were performed using two-sided Duncan’s multiple
246 range tests or paired t-tests. Since salivary melatonin and subjective sleepiness were also
247 collected during baseline and dark adaptation, these data were included in the analyses. For
248 all the cognitive tasks, data from the 5-hour computer light exposure was included in the
249 analysis. For the analysis of visual comfort, the five time points when it was carried out were
250 averaged to provide a global comparison between the two light settings.

251

252 **Results**

253 Salivary melatonin levels followed during baseline, dark adaptation and 5-h screen exposure
254 episode yielded a significant effect for *screen* ($F_{1,11} = 5.9$; $p = 0.045$), *time of day* ($F_{12,132} = 137.5$;
255 $p < 0.0001$), and the interaction *screen vs. time of day* ($F_{12,132} = 3.0$; $p = 0.041$, Figure 2, left
256 panel). The evening increase in endogenous melatonin levels was suppressed and rose later
257 under exposure to the LED screen compared to the non-LED screen, significant at the
258 following time points: 21:15h, 22:15h, 22:45h and 23:15h (*post-hoc* comparisons; *p* at least
259 < 0.04). Subjective sleepiness ratings taken at the same time intervals as for the salivary
260 melatonin assessments yielded a significant effect of *time of day* ($F_{12,132} = 25.9$; $p < 0.0001$,

261 Figure 2, right panel), but no significant effect for *screen* nor for the interaction *screen vs.*
262 *time of day*. However, a separate analysis of subjective sleepiness confined to the period
263 when the participants were asked to take a break and watch the movie (see methods),
264 revealed significantly lower sleepiness levels when the movie was displayed on the LED
265 screen compared to the non-LED screen (inset Figure 2, right panel, $p < 0.04$). Analysis of the
266 incidence of SEMs, an objective marker for sleepiness derived from the electrooculograms,
267 revealed significant differences for main factors 'screen' and 'night', although the interaction
268 was not significant (*screen*: $F_{1,11} = 26.2$; $p < 0.0004$, *time of day*: $F_{11,44} = 7.8$; $p < 0.0001$, *screen*
269 *vs. time of day*: not significant, Figure 3, left panel). A 2-way rANOVA for spectral EEG power
270 density during the KDTs revealed a significant interaction between the factors *screen* and
271 *EEG-derivation* in the frequency bins ranging from 1 to 7 Hz (p at least 0.05). Thus, EEG
272 power density in these frequency bins were collapsed into a frequency band of 1-7 Hz and
273 further analyzed with a 3-way rANOVA, which yielded a significant factor for *screen* ($F_{1,20} =$
274 6.7 ; $p < 0.02$), *derivation* ($F_{5,50} = 124.2$; $p < 0.0001$), a significant interaction *screen vs. EEG-*
275 *derivation* ($F_{5,50} = 2.6$; $p < 0.05$) and a significant interaction *EEG-derivation vs. time of day*
276 ($F_{20,200} = 2.9$; $p < 0.02$). Accordingly, exposure to the LED screen resulted in an attenuation of
277 frontal EEG activity in the range from 1-7 Hz (Figure 3, right panel), which was not observed
278 in other derivations.

279 Similarly, sustained attention (as indexed by reaction times in the GO/NOGO performance)
280 was significantly improved in the LED screen as compared to the non-LED screen condition,
281 as indicated by a significant effect of *screen* ($F_{1,11} = 12.2$; $p < 0.04$), *time of day* ($F_{11,44} = 7.8$;
282 $p < 0.02$) and the interaction term *screen vs. time* $F_{12,132} = 3.0$; $p = 0.041$; *post-hoc* comparisons
283 at 22:15h and 23:15h: $p < 0.04$, Figure 4, left panel). The time course of the participant's
284 performance in the time reproduction task for the 10-s interval is illustrated in Figure 4,

285 middle panel. A significant factor *screen* ($F_{1,11} = 5.8$; $p < 0.04$), *time interval* (5, 10, 15s; $F_{2,22} =$
286 81.4 ; $p < 0.0001$), and the interaction *screen vs. time of day* ($F_{3,33} = 3.7$; $p < 0.03$) was elicited.
287 *Post-hoc* testing revealed a significantly faster reproduction (i.e. a more pronounced
288 underestimation of reproducible time intervals) under the LED screen condition at 21:30h
289 ($p < 0.04$). Similar results as for time reproduction were found for time production (data not
290 shown). In the learning task, the percentage of correctly recognized 'old' word pairs did not
291 significantly differ between the LED and the non-LED screen (data not shown). Interestingly,
292 volunteers identified more newly introduced word pairs during the recall session under the
293 LED screen condition as compared with the non-LED screen condition, as indicated by a
294 significant interaction *screen vs. time of day* ($F_{3,30} = 3.6$; $p < 0.03$), with a significant *post-hoc*
295 comparison at 21:30h ($p < 0.02$, Figure 4 (right panel)).

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

299

300 **Discussion**

301 Evening exposure to a LED-backlit computer screen resulted in attenuated salivary melatonin
302 and sleepiness levels, with a concomitant increase in cognitive performance associated with
303 sustained attention and with working and declarative memory. Given that the measured
304 illuminance levels and the subjective ratings of visual comfort of both LED and non-LED
305 screens were very similar, we assume that the disparity of the light's spectral composition
306 emitted by the LEDs was the major factor contributing to the observed effects. Indeed, the
307 LED-backlit screen emitted 3.32 times more light in the blue range between 440 and 470 nm
308 than the non-LED-backlit screen. Our data correspond with previous observations that

309 human circadian physiology and alertness levels are particularly sensitive to short-
310 wavelength light (5, 6, 8, 9, 17, 18, 24, 28, 31). New in current findings is that this effect
311 occurs with non-monochromatic light sources at relatively low light levels, and that it
312 impinges on sustained attention and performance during higher cognitive tasks involving
313 working and declarative memory systems. Whether the observed faster estimation of time
314 and the better recognition of new interspersed word pair items during the recall session is
315 related to the enhanced alertness levels or represent an effect on brain structures involved
316 in memory *per se*, needs to be further explored by functional imaging data. In any event, we
317 could not find a significant correlation between alertness and memory performance levels,
318 which rather points to a weak association between these two measures. Recent fMRI
319 experiments have shown that light independently affects alertness-related subcortical
320 structures in the brainstem as well as higher order cortical areas, including the fronto-polar,
321 lateral prefrontal cortex, and premotor cortex, the intraparietal sulcus, insula, cerebellum
322 and thalamus, all of which are known to be involved in executive control and working
323 memory (29). Interestingly, many of these brain structures play an important role in
324 'duration estimation' or explicit timing in the supra-second range (10) as well as in
325 performance requiring more long-term memory stores for declarative learning (21, 33). We
326 may speculate that blue-enriched light emitted by the LED backlit screen had beneficial
327 effects on working memory demands as indexed by a faster production and reproduction of
328 time intervals in the supra-second range (5-15 s) as well as on declarative memory, as
329 indexed by a the better recognition of newly acquired word pairs. Thus, our effects point to
330 a superiority of the LED-backlight screen in terms of enhancing alertness and cognitive
331 performance in the evening.

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

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

352 If one evening can result in later sleep times, as might be predicted from our data, then
353 continued daily computer use may delay more and more. Whether computer screens
354 contribute to a late chronotype requires further investigation (13, 15). Indeed, although the
355 chronic use of LED screens immediately prior to sleep may result in circadian phase-shifts

356 and alterations in sleep, we have insufficient studies that have looked at these long-term
357 effects. Thus, possible detrimental effects of LED screens are as yet unclear. Our data
358 suggest that rather short exposures (5 hours) at low light intensities (<100 lux, at a distance
359 of 50 cm) with a relative high amount of short-wave length LED light can evoke circadian
360 melatonin responses and behavioral changes as measured in alertness levels and cognitive
361 performance. However, this should be viewed with caution since the spectral profiles of the
362 two screens varied in other ways than just short-wavelength emission. Another study
363 limitation is the fact that this study was conducted only on men. This was mainly due to the
364 fact that menstrual phase and use of oral contraceptives could alter, for instance, melatonin
365 secretion[for a review, see (2)]. Future studies are needed to investigate these effects in
366 women. Furthermore, technical progress is needed to build LED devices, which may adapt
367 their emitted light spectrum dynamically according to the time of day, such as the f.lux
368 program (stereopsis.com) and even better, to the user's sleep-wake timing. Ideally,
369 computer screens would therefore not only be an interface for electronic information
370 exchange, but also help to provide essential light information to the circadian timing system
371 by positively supporting circadian alignment with individually timed backlight changes of the
372 spectral profile of the computer screen.

373

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379

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463 Munich Chronotype Questionnaire with the Horne-Ostberg's Morningness-Eveningness
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469 **Figure legends**

470 **Figure 1.** Upper panel: left hand side: photograph of the Non-LED computer screen [HP
471 LP2475w, CCFL (Cold Cathode Fluorescent Lamp)], right hand side: photograph of the LED
472 computer screen (HP LP2480zx LED). Lower panel: Spectral composition [light wavelength by
473 irradiance; Watt/(sr x m²x nm)] of light emitted from the LED computer screen (blue line)
474 and the non-LED screen (red line). Inset: Blow-up of the spectral composition in the
475 wavelength range of 410-500 nm. The photon flux for the LED backlit screen was 2.1×10^{13}
476 photons/(cm²*s) in the wavelength range of 454 and 474 nm and 0.7×10^{13} photons/(cm²*s)
477 in the wavelength range of 454 and 474 nm for the non-LED backlit screen.

478

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

486

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

492

493 **Figure 4.** Time course of cognitive performance during the screen exposure episode:
494 sustained attention as assessed by the GO/NOGO paradigm, working memory/attention as
495 assessed by a time perception task and declarative memory as assessed by a word pair

496 learning task. Mean values + or – SEM, n=13). Filled black dots represent results of the LED
497 computer screen condition, open dots indicate data of the non-LED computer screen
498 condition.

499

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

506

507

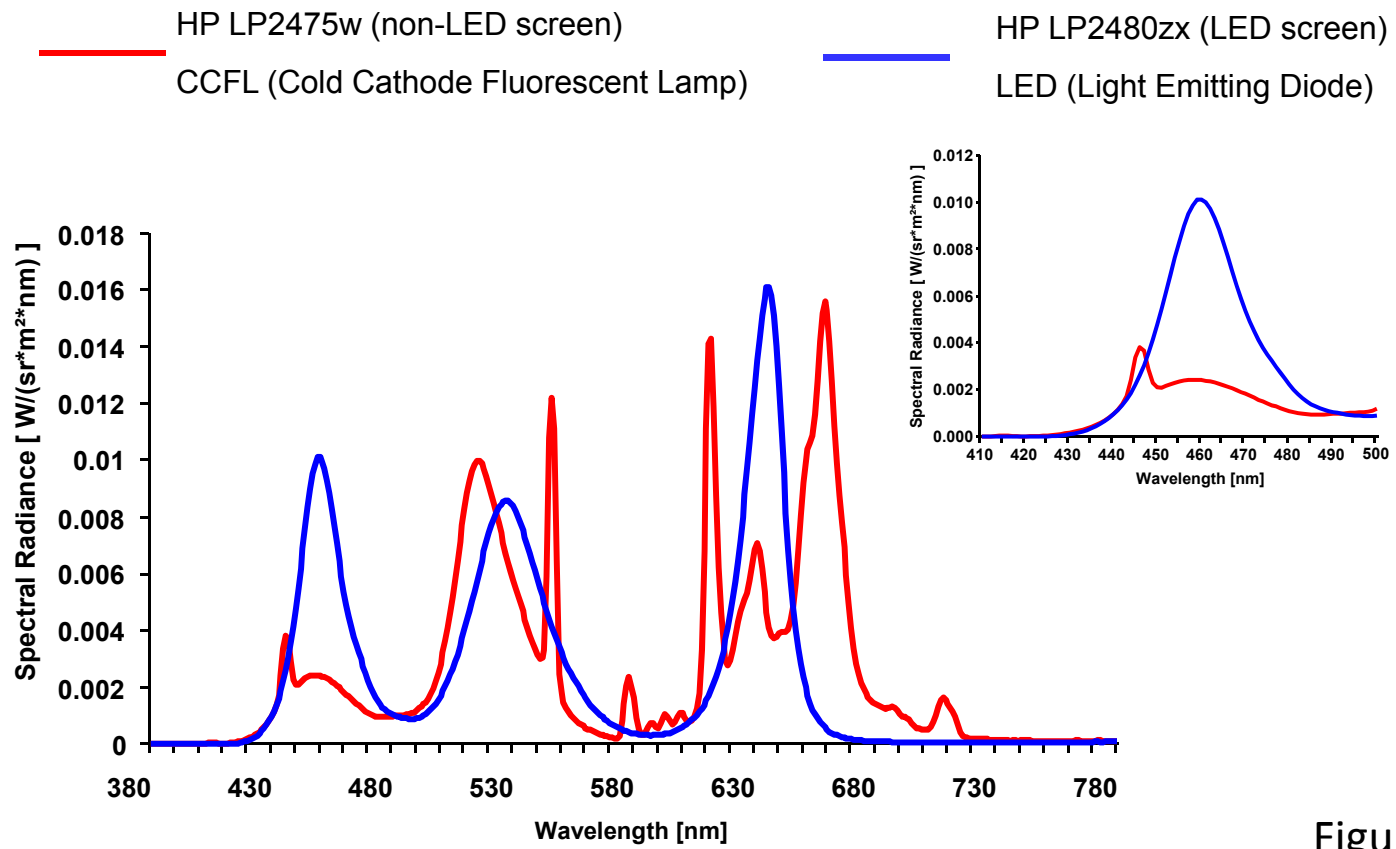
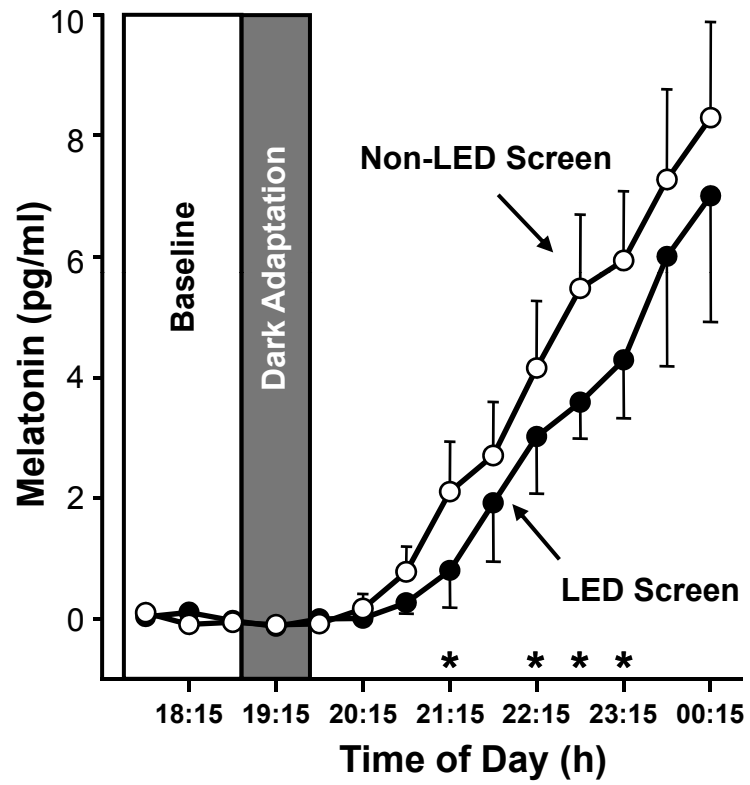


Figure 1

Salivary Melatonin



Subjective Sleepiness

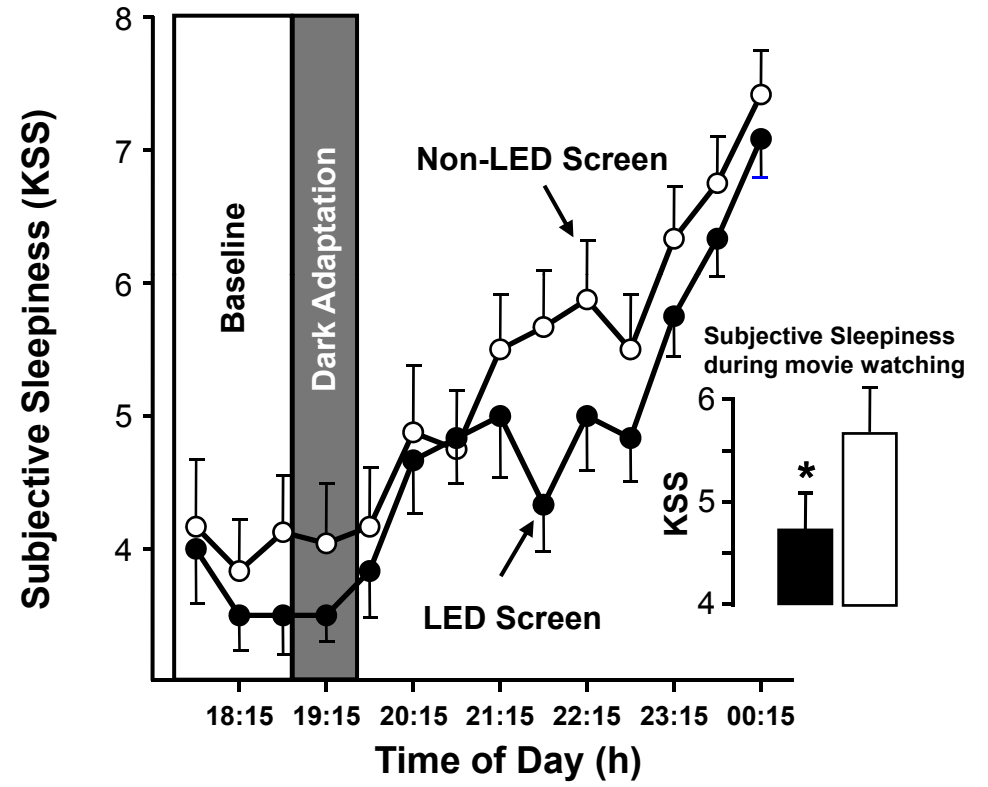
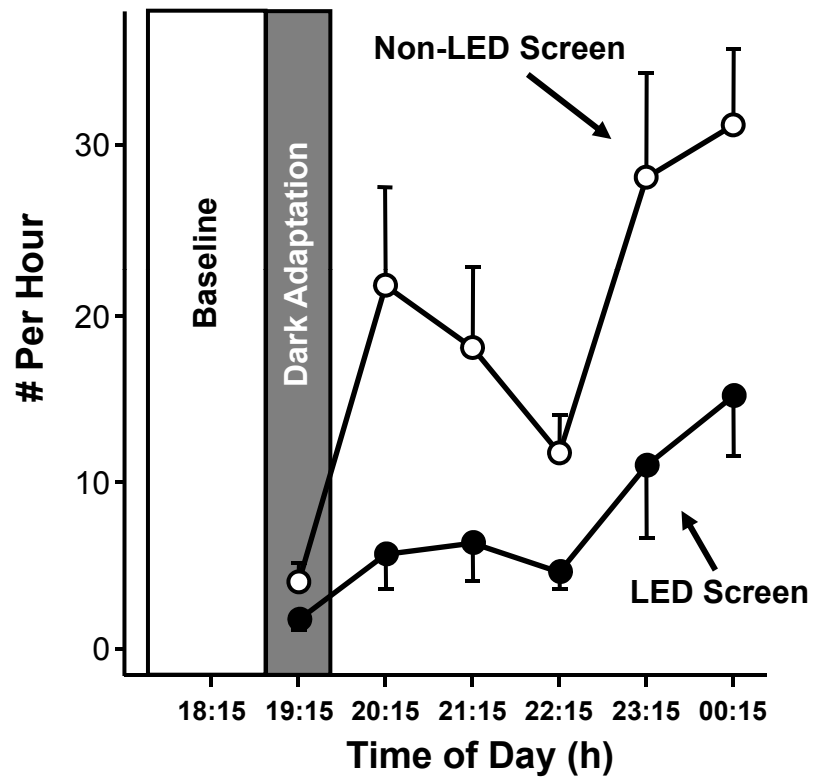


Figure 2

Slow Rolling Eye Movements



Frontal EEG Activity (1-7 Hz)

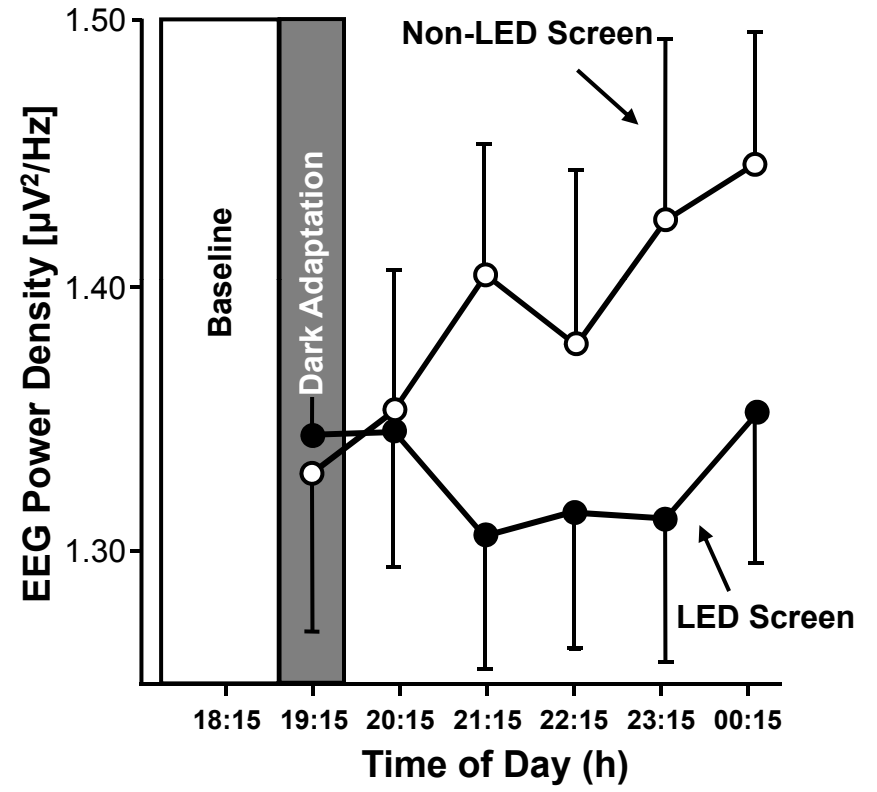


Figure 3

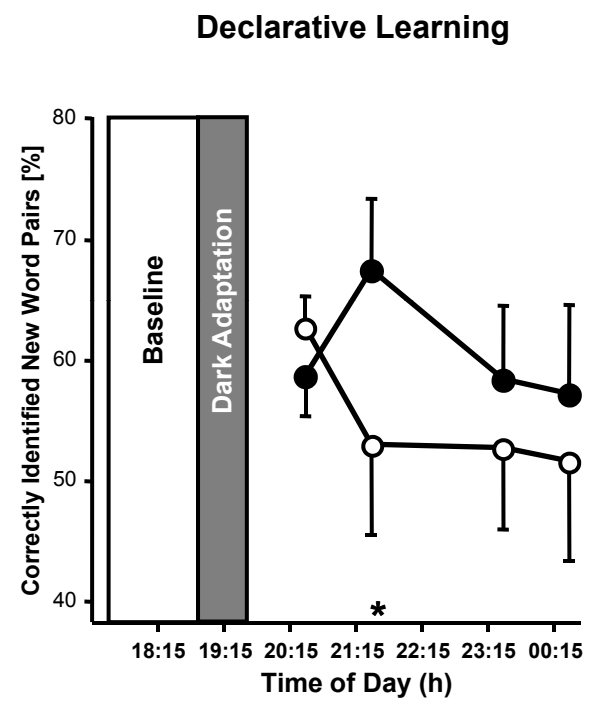
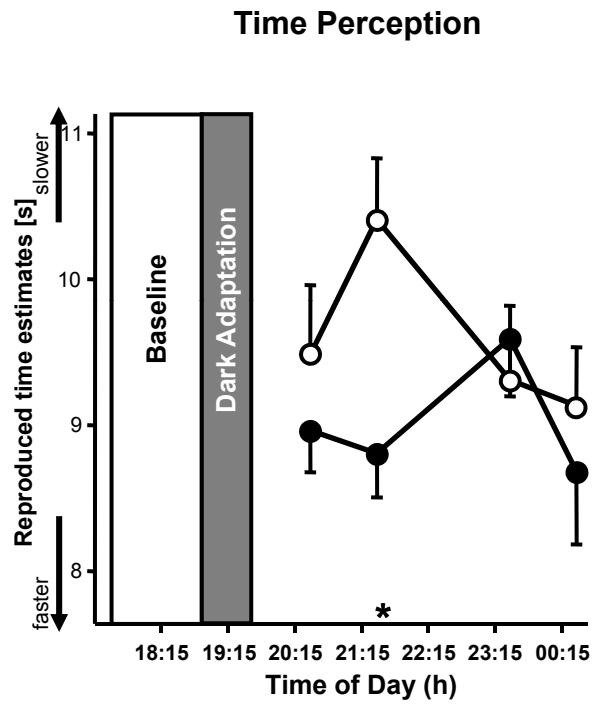
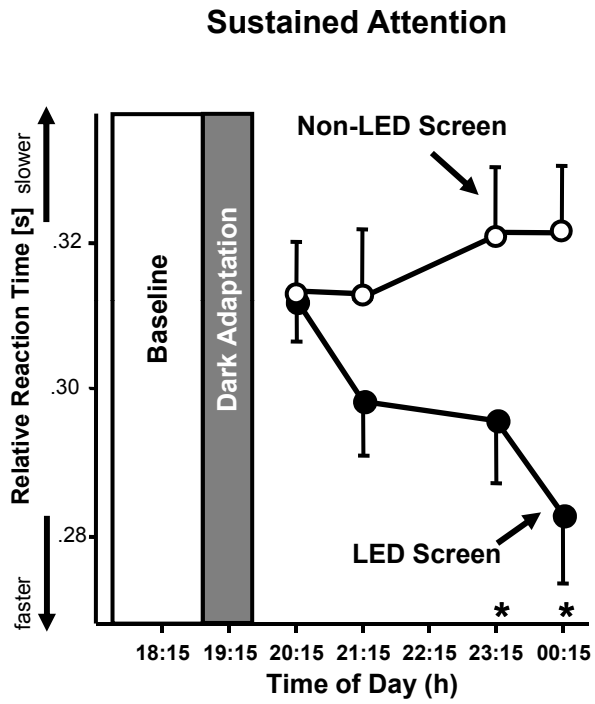
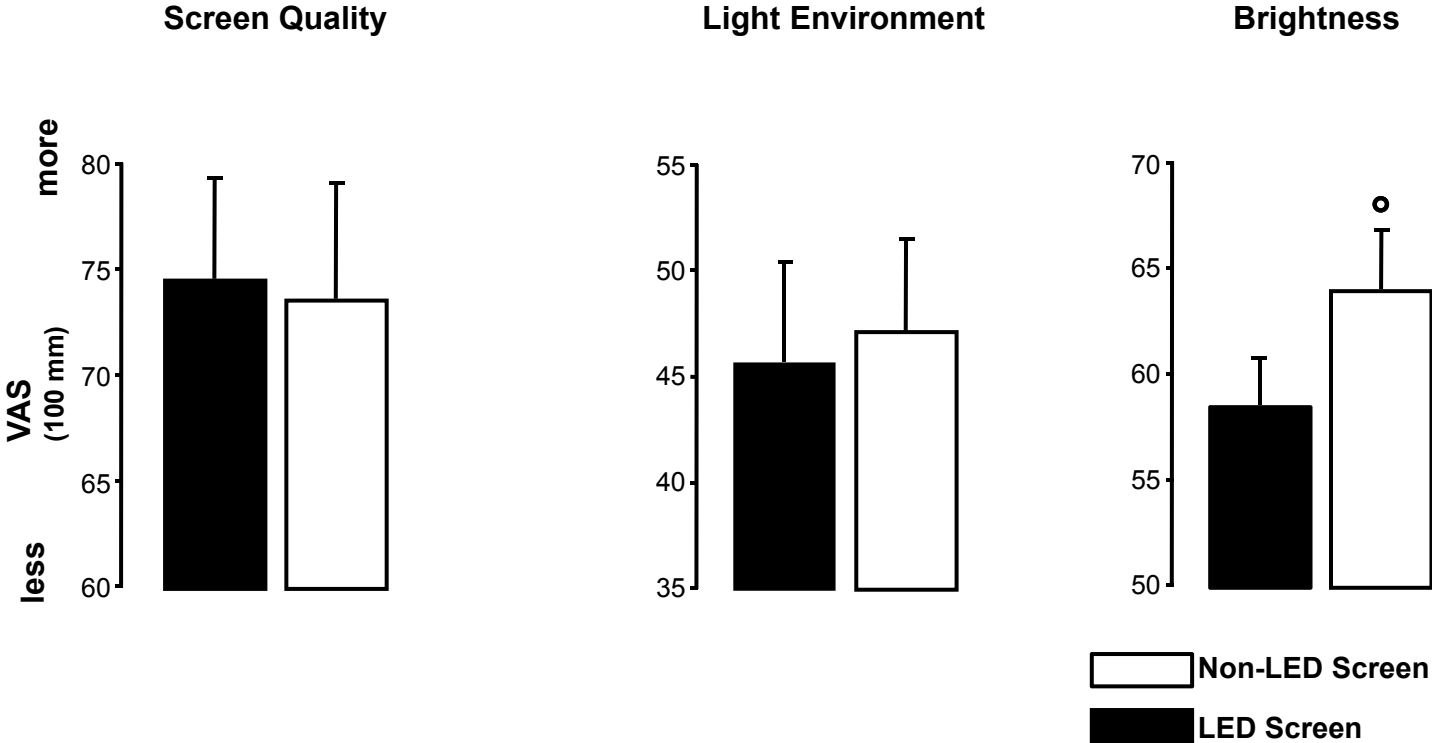


Figure 4

Visual Comfort Questionnaire



Supplemental Figure