Higher light intensity induces modulations in brain activity even during regular daytime working hours

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Higher light intensity induces modulations in brain activity even during regular daytime working hours

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We investigated the effect of exposure to bright white light as compared to a commonly experienced illuminance (1000 lx vs. 200 lx at eye level, 4000 K) on electroencephalography spectral power density during daytime. Spectral power density was measured during one hour of exposure in the morning and in the afternoon. Results showed a lower relative power density in the theta range under bright light. In the morning, relative alpha power was also lower under exposure to 1000 lx. The current findings extend earlier results on the effect of illuminance on alertness and arousal in the late evening and at night. Moreover, they largely corroborate results on subjective experience and sustained attention during daytime, and together suggest higher alertness under brighter light even for daytime exposure in everyday situations.

1. Introduction

Research has shown that light is important for mental well-being, health and performance.[1–7] Light enables vision, but also plays an important role in human everyday functioning via non-image forming processes. A large body of research has, for instance, shown that light can induce instantaneous changes in alertness, mood, cognition and behaviour. The effect of light on peoples' affective, cognitive and physiological functioning is dependent on – among others – the intensity level employed. To date, numerous studies have shown that exposure to a higher illuminance can increase feelings of alertness, result in faster responses on sustained attention tasks, suppress melatonin secretion, increase heart rate and core body temperature.[8–17] Most of the studies of the acute activating effect of bright light exposure on subjective and objective indicators of alertness and arousal have been performed in the late evening and at night or during daytime after substantial sleep and/or light deprivation. Together, these studies indicate that bright as compared to dim light can benefit persons under conditions of high circadian and/or homeostatic need for sleep, and after adaptation to darkness or very low light levels.

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A few recent studies have also demonstrated acute alerting effects of exposure to more intense light on healthy day-active persons during regular working hours. A recent field study showed that the amount of light received at the eye during individuals' daily routine was a significant predictor for feelings of vitality on an hourly basis.[18] Moreover, results of a laboratory study revealed that diurnal exposure to a higher illuminance affects human daytime functioning in the absence of sleep deprivation and prior adaptation to darkness or dim light.[19] Not only did bright light exposure increase subjective alertness and vitality as compared to commonly experienced light levels during daytime hours, it also improved performance on an auditory vigilance task and increased physiological arousal assessed with heart rate and heart rate variability (HRV). In this paper, we report on the electroencephalography (EEG) data collected during the same laboratory study, exploring the effect of bright white light on brain activity during daytime. EEG spectral power density has been used as indicator of alertness in earlier studies and has been shown to be related to subjective measures of alertness and sleepiness, and objective measures of sustained attention and cognitive performance.[20–28]

Several studies performed at night have shown modulations in awake EEG during exposure to a higher illuminance, particularly in the theta and alpha range.[10,29–33] A few studies also investigated the effect of bright versus dim light exposure on EEG during both nighttime and daytime.[8,32] Rüger *et al.*, for example, showed that exposure to bright light (5000 lx), as compared to dim light (<10 lx) resulted in lower slow wave EEG activity (3–4.5 Hz) with eyes closed in the afternoon and at night.[32] In the afternoon, however, the effect of bright light on slow wave EEG activity was less pronounced than at night. Moreover, no effect of bright light on alpha power was reported in the afternoon, except for an effect opposite to that at night, i.e. a decrease in power density, in the 10–10.5 Hz frequency bin with eyes closed.[32] Badia *et al.* showed that while nighttime exposure to a high illuminance (>5000 lx vs. 50 lx) resulted in higher levels of beta power, there were no significant effects on EEG during daytime.[8] It should be noted that the number of participants in the daytime sessions was small ($N = 8$) in this study. Similarly, Daurat *et al.* revealed that nocturnal exposure to a high illuminance (>2000 lx vs. 150 lx at eye level) resulted in a significantly larger difference in alpha power measured during eyes closed versus eyes open, yet showed no significant differences between the two lighting conditions employing a small sample size ($N = 8$) during daytime.[30] In contrast, Kaida *et al.* provided indications that bright light exposure in the early afternoon modulates brain activity.[34] Their results showed that exposure to natural bright light for 30 minutes after lunchtime resulted in lower alpha power during eyes open and lower theta power during eyes closed as compared to artificial dim light (<100 lx at eye level). It should be noted, however, that with the use of natural light through a window not only the illuminance but also other factors vary, suggesting that the effects may be confounded with effects of colour temperature, dynamic light conditions and a view to the outside. In addition, a neuroimaging study by Vandewalle *et al.* employing functional magnetic resonance imaging (fMRI) reported increased activity in areas related to alertness and cognition while subjects engaged in a cognitive performance task under daytime exposure to bright light (>7000 lx for 21 minutes of exposure after prior dark adaptation) as compared to darkness (<0.01 lx).[35]

In this study, we explored the effect of daytime exposure to a high illuminance (1000 lx at the eye) on EEG activity as compared to a commonly experienced

illuminance during regular working hours (200 lx at the eye[18]). We investigated the effect of exposure to bright light on theta, alpha and beta power density during regular daytime situations (i.e. no sleep deprivation or prior exposure to darkness or dim light). Based on earlier research to the effects of light on the awake EEG, we expected effects on EEG particularly in the theta and alpha range, with lower power densities in the bright light condition.[10,29–33,36,37] Since EEG power density seems to show diurnal variations,[20,38–40] we distinguished between morning versus afternoon exposure to explore potential moderations in the effect of light by time of day. In addition, the development of EEG power density in the theta, alpha and beta range was investigated throughout an hour of light exposure to 1000 lx versus 200 lx at the eye. This allowed us to assess whether modulations in EEG occurred immediately with light onset – and persisted during the light exposure – or showed delayed or otherwise duration-dependent effects. Moreover, EEG was assessed in different brain regions (i.e. frontal, central, parietal and occipital) to explore whether effects of illuminance on EEG power density were dependent on cortical area. We thus investigated whether exposure to bright light during regular daytime hours induces modulations in brain activity measured with EEG, and explored potential modulations by time of day, duration of exposure and cortical area.

2. Method

2.1. Design

A 2×2 mixed design was applied to explore the effect of illuminance (200 lx vs. 1000 lx at eye level) for morning versus afternoon exposure. Participants came to the laboratory for two to four visits on separate days and experienced one lighting condition per day. When persons participated twice, they were exposed to 1000 lx in one session and to 200 lx in the other session both at the same time of day (local clock time), i.e. the lighting condition was manipulated within subjects. When persons participated four times, both lighting condition and time of day were manipulated within subjects: they experienced all experimental conditions. During three visits, participants were exposed to both lighting conditions at the same time of day as well as to one of the lighting conditions at another time of day. Participants were randomly assigned to the order of experimental conditions. There was no daylight contribution in the room during this experiment.

2.2. Participants

Thirty-two students participated in this experiment (consisting of 83 sessions in total), of which 19 were male and 13 female ($M_{age} = 22$ years, SD = 4.0, range 18–35 years). The EEG data of one of these participants were excluded due to poor signal quality in all four sessions. None of these participants were extreme chronotypes according to the Munich Chronotype questionnaire (MCTQ[41]), had travelled to a different time zone two weeks prior to the experiment or had complaints about their general health. Twenty people participated in two sessions (both lighting conditions in the morning or afternoon); seven people participated in four sessions (both lighting conditions in the morning and in the afternoon); five participated in three sessions. On average, they participated in 2.6 (SD = 0.8) conditions – always on separate days – with, on average, four days between each session. Within participants, the morning and afternoon sessions were scheduled at the same time of day (9 am or 11 am, and 1 pm or 3 pm, respectively). The distribution across experimental conditions is described in Table 1. The study was approved by the review board of the Human Technology Interaction group in Eindhoven.

2.3. Setting

The room in which the experiment took place was a simulated office environment at the Eindhoven University of Technology in the Netherlands and had a size of 3.6 m by 3.2 m. The main furnishings of the room consisted of a desk with computer, chair and a cabinet. The walls and ceiling were off-white and had a reflectance of 87%, the floor was grey-blue with a reflectance of 19% and the desk was grey and had a reflectance of 39%.

The room was equipped with surface-mounted Philips Strato luminaires mounted on the walls and ceiling. Each luminaire measured 1.2 m × 1.2 m and contained six fluorescent tubes of 28 W, of which three tubes were of 2700 K (TL5-28 W/827) and three tubes were of 6500 K (TL5-28 W/865). The luminaires had a translucent two layer polymethyl-methacrylate cover with an integrated diffuser to blend the two lamp types. The spectral power distribution (SPD) and colour rendering index (CRI) were measured with a calibrated spectroradiometer (JETI Specbos 1201) at eye level (height 1.20 m) aimed at the wall in the gaze direction of participant. The SPD of the lighting at 4000 K is depicted in Figure 1. The CRI at 4000 K was $R_a = 86$.

During the baseline phase and throughout the experiment, three ceiling-mounted luminaires provided basic room illumination (118 lx at eye level (photon density: 9.18×10^{13} photons/cm^2/second; irradiance: 34 μW/cm^2) and 200 lx at the desk). In addition to this baseline setting, a wall-mounted luminaire was turned on when the experimental conditions started. In the 200 lx condition, settings were such that this resulted in a total of 200 lx at the eye (photon density: 1.63×10^{14} photons/cm^2/second; irradiance: 61 μW/cm^2) and 233 lx at the desk. In the 1000 lx condition, this resulted in 1000 lx at the eye (photon density: 8.04×10^{14} photons/cm^2/second; irradiance: 300 μW/cm^2) and 649 lx at the desk. In both conditions, the lighting was set at 4000 K. The height at eye level used in this study was 1.20 m.

Table 1 Overview number of participants in experimental conditions[a]

	200 lx		1000 lx	
Males	Females	Males	Females	
Morning	12	10	13	10
Afternoon	10	9	12	7

[a]Total $N = 32$, of which 7 participated in all four conditions.

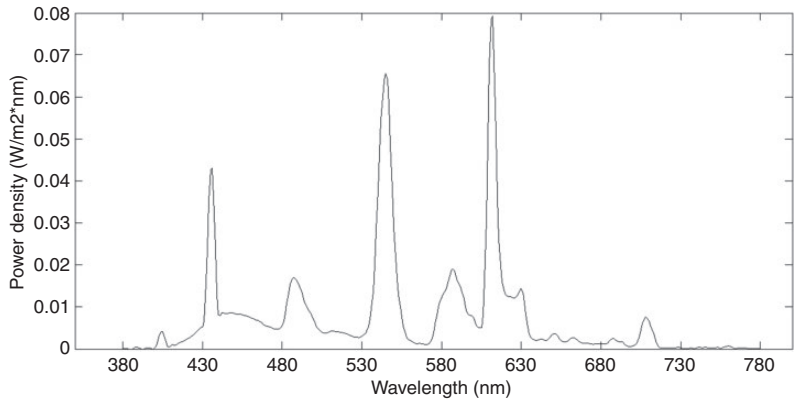

Figure 1 Spectral power distribution measured at eye level in the 1000 lx (4000 K) condition

2.4. Procedure

Prior to the start of the first session, participants signed a consent form and completed a questionnaire to assess personality traits and demographic data. At the start of each session, participants completed a questionnaire on their sleep timing during the previous night, time spent outside, travelling time outside and whether they had had coffee and/or eaten something one hour before the experiment. Each session consisted of a baseline phase and an experimental phase. During this baseline phase, participants applied electrodes for the heart rate and skin conductance measures according to the instructions given by the experimenter. Subsequently, the procedure of applying the EEG electrodes was explained and the experimenter placed the electrodes on the participant's scalp. After applying the electrodes, participants read the instructions for the tasks and the baseline measurements started.

Each session consisted of five measurement blocks (Figure 2). The first measurement block took place during the baseline phase; the remaining four measurement blocks (blocks 1 to 4) comprised the experimental phase. Each block started with an EEG protocol: participants focused on a dot on the screen for two minutes and subsequently closed their eyes for two minutes to measure brain activity with eyes open and eyes closed. After the four-minute EEG protocol, participants engaged in a simple reaction time task and a more complex cognitive performance task. At the end of each measurement block, participants filled in a short questionnaire to measure their sleepiness, vitality and mood. In addition, at the end of each session, participants completed questions concerning their appraisals of the lighting and the room. Every session lasted 90 minutes and the participants received a compensation of 15 Euros per session. The study took place from June to September 2010.

2.5. Measures

Repeated self-report, task performance, EEG, heart rate and skin conductance measures were applied in each session.

2.5.1. Physiological measures

EEG power density was measured at positions F3, F4, C3, C4, P3, P4, O1 and O2 according to the international 10-20 system with Cz as common reference.[42] The EEG signals were measured at a sampling frequency of 250 Hz, high-pass filtered at 0.5 Hz and low pass filtered at 30 Hz. BMC acquisition software (Xplicare, Brainmarker, the Netherlands) was used for data acquisition, filtering and display of the signals. At the start of each session, the electrode impedance was checked to be less than 10 kΩ. To minimize poor signal quality, artefacts in the EEG signals were removed based on the work of Van de Velde *et al.*,[43] using Matlab 7.11.0. As a first step of the artefact detection, amplitudes higher than 70 μV or lower than − 70 μV were removed. Subsequently, the two-minute measurement periods during the eyes open parts were divided into two-second epochs and each epoch was inspected for outliers based on its minimum, maximum and maximum slope. The data of a two-second epoch with one or more of these variables having a value more than three standard deviations from the median of all epochs in the two-minute period were recorded as missing values. After artefact detection, the SPD was computed for each 2-second epoch using a Fast Fourier Transformation (FFT) with Hamming window in Matlab. Subsequently, EEG powers were averaged over the theta (4–8 Hz), alpha (8.25–12 Hz) and beta (12.25–30 Hz) ranges (in $\mu V^2/Hz$) for each epoch. Aggregated mean power scores for each two-minute eyes open measurement were computed when no more than 25% of the epochs had a missing value, i.e. averages were computed for periods of at least 90 seconds.

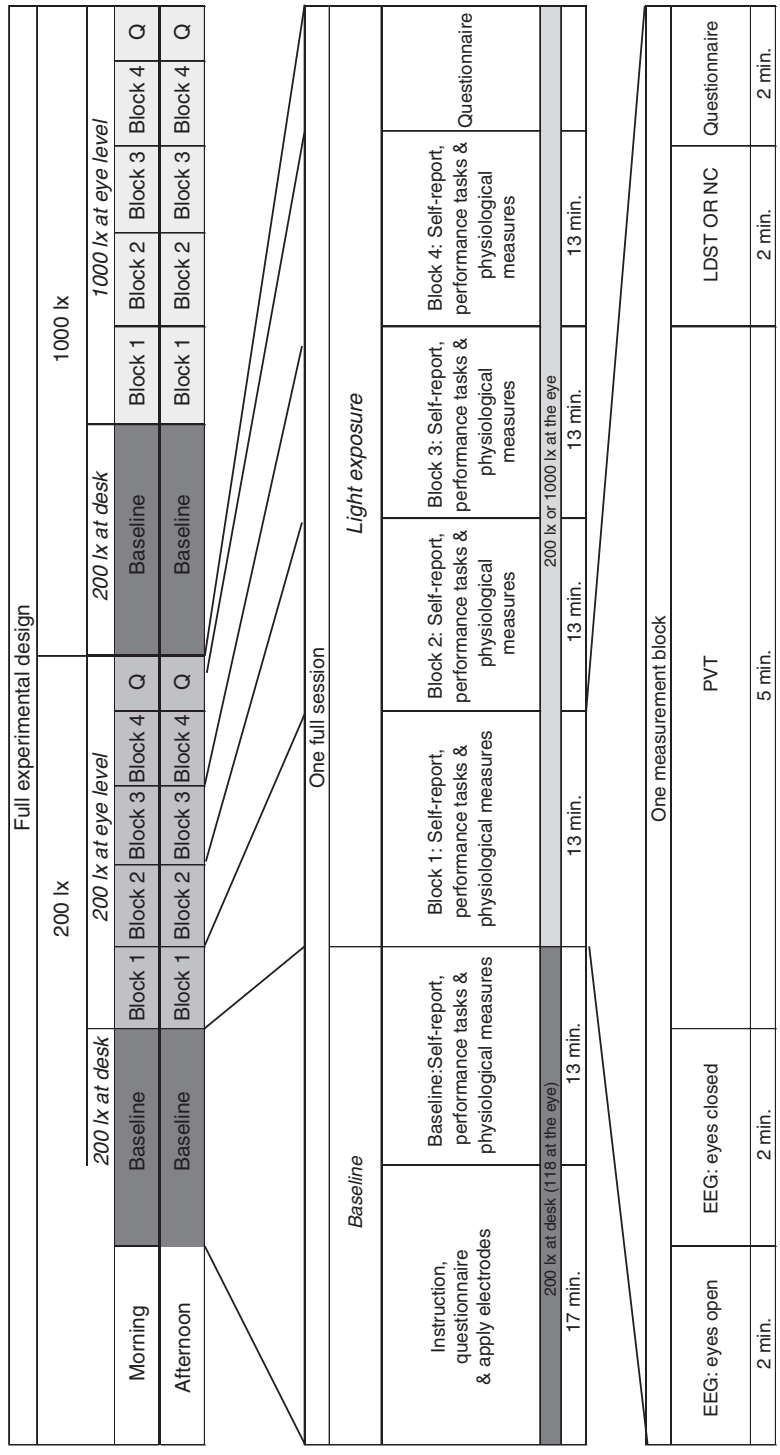

Figure 2 Overview of the procedure of the experiment

To correct for inter- and intra-individual differences, powers in the theta, alpha and beta range during the light exposure were computed relative to the corresponding baseline power, i.e. power measured at the start of each session. Therefore, theta, alpha and beta powers represent the power as percentage of corresponding baseline. The relative powers were inspected for extreme values: percentages below 20 and above 500 (i.e. a factor of 5 from the baseline) were assumed to be invalid and coded as missing. In addition, outliers were removed based on three standard deviations from the mean to meet requirements for a normal distribution. In total, less than 7.5% of the data was coded as missing for the different EEG measures after all steps (specifically, theta: 6.2%, alpha: 7.2% and beta: 7.0%).

Heart rate, HRV and skin conductance were measured continuously during the experiment using TMSi software. As mentioned in the Introduction, the results of these measures have been reported earlier.[19,44]

2.5.2. Self-report measures

Subjective sleepiness was assessed with the Karolinska Sleepiness Scale (KSS[21]). Subjective vitality and tension were measured with six items selected from the activation–deactivation adjective checklist.[45] In addition, positive affect ('happy') and negative affect ('sad') were each probed with a single item. Moreover, participants' evaluation of lighting condition and office environment as well as their beliefs regarding the effects of the lighting conditions on work performance and mood were assessed at the end of each session. Effects of illuminance (1000 lx vs. 200 lx) on these self-report measures have been reported in an earlier publication.[19,44]

2.5.3. Task performance

In the baseline and in all four measurement blocks of the experimental phase, a five-minute auditory Psychomotor Vigilance Task (PVT) was employed to measure sustained attention.[46] In addition, in blocks 1 to 3, a visual Letter Digit Substitution Test (LDST[47]) was administered. In the baseline and last measurement block, the Necker cube pattern control test was administered after the auditory PVT.[48] Effects of the lighting conditions on task performance have also been discussed elsewhere.[19,44]

2.6. Potential confounding variables and personality traits

Sleep onset and sleep offset, time spent outside, travelling time outside and whether participants had coffee and/or ate something one hour before the experiment were investigated at the beginning of each session. Personality traits were assessed prior to the first session in which the subject participated. Subjective light sensitivity was measured with three items developed for the current study: 'How much trouble do your eyes give when you are exposed to bright light?', 'How much do you suffer from headaches when you are exposed to bright light?', and 'How often do you wear sunglasses because light is too bright' ($\alpha = 0.63$). Trait subjective vitality was measured with the trait level subjective vitality scale ($\alpha = 0.90$).[49] General health was assessed with five items from the Dutch version of the SF-36 Health Survey (General health perception subscale of the RAND-36[50]). Sleep quality was measured with the Pittsburg Sleep Quality Index (PSQI[51]) and chronotype was assessed with the Dutch translation of the MCTQ.[41]

2.7. Statistical analyses

Statistical analyses were performed with IBM SPSS statistics software version 20. Due to the nested structure of the data, Linear Mixed Model (LMM) analyses were performed to test the effect of illuminance on the relative theta, alpha and beta power densities. In these LMM analyses, lighting condition (200 lx vs. 1000 lx), cortical area

(frontal, central, parietal vs. occipital), measurement block (block 1–block 4) and time of day (morning vs. afternoon) were added as fixed factors and the EEG measures as dependent variables (separate LMM analyses were run for each dependent variable). The two-way interactions of lighting condition with cortical area, time of day and measurement block were added to the model to explore whether the effect of illuminance was moderated by cortical area, time of day or time in session. In addition, the two-way interaction between cortical area and time of day and the three-way interaction between lighting condition, cortical area and time of day were added to control for potential time-dependent differences in cortical areas. Hemisphere was only added as nesting variable for cortical area, but not included as fixed factor to the final model to reduce complexity. Note that analyses with hemisphere added as a factor revealed no significant main effect of hemisphere nor significant interaction effects between lighting condition and hemisphere (data not shown).

In all analyses, participant was added as independent random variable to group the data per participant, i.e. to indicate that the same participant was measured multiple times. In addition, cortical area was added as a repeated random variable (nested within hemisphere, which in turn was nested in measurement block per session for each participant), to indicate that the relative power density on the different cortical areas was measured in parallel at both the left and right hemisphere during each measurement block in a session. An unstructured residual covariance matrix was used to model potential variance and covariance between the residuals of different channels during each block as this resulted in the best fit of the null models (i.e. an unconditional model with no predictors). This models potential covariance in error between the relative powers measured at the different cortical areas within the left or right hemisphere (e.g. between F3 and C3 or between C4 and O2) and potential variance between residuals within one cortical area between hemispheres (e.g. between F3 and F4 or between O1 and O2) over time in each session. Light sensitivity, chronotype, trait vitality and global sleep quality were added as covariates to the hierarchical models to control for these person characteristics. General health and gender were not added to the models to avoid multicollinearity as these variables correlated ($r > 0.3$) with the other covariates. Note that reported contrasts for interaction effects always refer to post hoc comparisons with Bonferroni correction.

3. Results

We will report on the effect of illuminance, cortical area, measurement block and time of day on the relative power in the theta, alpha and beta range.

3.1. Baseline comparisons

Baseline comparisons of the different EEG measures revealed no significant differences between the lighting conditions during the baseline phase ($p > 0.10$), except for a non-significant trend for an interaction between lighting condition and time of day on theta power at baseline ($F(1,124) = 2.85$; $p = 0.09$). *Post hoc* comparisons, however, revealed no significant differences (all $p > 0.10$).

3.2. Effects on relative power in theta, alpha and beta range

Cortical area had a significant main effect on the relative power in the alpha and beta range ($F(3,590) = 11.58$ and $F(3,585) = 6.72$, respectively, both $p < 0.01$). Alpha was higher compared to baseline at the parietal and occipital sites than at the frontal and central sites (Table 2). In contrast, the relative beta power was higher at the frontal site compared to the other areas (Table 2). While these

differences over the scalp during the light exposure occurred for alpha and beta, there was no significant main effect of cortical area on the relative power in the theta range ($F(3,584) = 1.92$; $p = 0.13$). However, there was a non-significant trend for time-dependent differences in theta between the cortical areas during the light exposure ($F(3,584) = 2.13$; $p = 0.10$). *Post hoc* comparisons revealed significant differences in the relative theta power between the areas in the morning sessions ($F(3,563) = 2.90$; $p = 0.04$), but not in the afternoon sessions ($F(3,584) = 1.31$; $p = 0.27$).

Lighting condition had a significant main effect on the relative power in the theta range, but not on the relative alpha or beta power (Table 3). Theta was lower in the 1000 lx condition compared to the 200 lx (at the eye). The interaction between lighting condition and cortical area was also significant ($F(3,584) = 5.16$; $p < 0.01$), indicating that this effect was moderated by cortical area. *Post hoc* comparisons showed that the difference in theta between the lighting conditions was most pronounced at the frontal ($F(1,503) = 19.35$; $p < 0.01$) and occipital sites ($F(1,525) = 3.96$; $p = 0.05$), and was not significant at the central ($F(1,540) = 2.42$; $p = 0.12$) and parietal areas ($F(1,510) = 0.35$; $p = 0.56$) (Figure 3). The interaction between lighting condition and cortical area was not significant for alpha ($F(3,590) = 1.62$; $p = 0.18$) nor beta ($F < 1$, ns).

Measurement block had a significant main effect on the relative alpha power ($F(3,584) = 11.28$; $p < 0.01$). While the relative theta and beta power did not significantly change with time in session ($F(3,564) = 1.01$; $p = 0.39$ and $F(3,583) = 2.06$; $p = 0.11$, respectively), alpha was lower in

Table 2 Relative power density per cortical area

	Theta		Alpha		Beta	
	EMM	SE	EMM	SE	EMM	SE
Frontal	107.46	2.75	115.79	4.21	113.27	2.71
Central	109.39	2.59	112.49	4.21	108.13	2.54
Parietal	110.51	2.60	121.56	4.26	108.13	2.48
Occipital	109.50	2.58	118.03	4.24	105.75	2.62

EMM: estimated marginal means; SE: standard error.

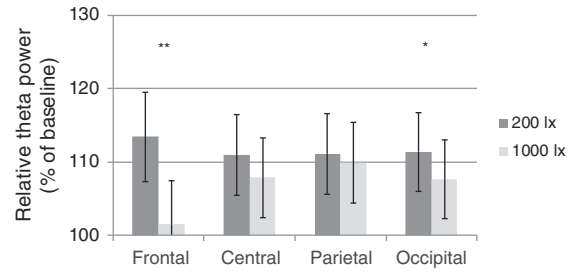

Figure 3 Relative theta power per cortical area for the 200 lx and 1000 lx conditions with the 95% confidence interval

Table 3 Results LMM analyses for relative power density per frequency band[a]

	200 lx		1000 lx		Statistics			
	SE	EMM	SE	F	df	*p*	R^2	
Relative power density								
Theta (% of baseline)	**111.71**	**2.68**	**106.72**	**2.68**	**8.68**	**(1553)**	**<0.01**	**0.03**
Alpha (% of baseline)	118.64	4.24	115.30	4.24	2.42	(1,572)	0.12	0.05
Beta (% of baseline)	109.36	2.53	108.27	2.53	.58	(1,575)	0.45	0.02

EMM: estimated marginal means; SE: standard errors.
[a]Significant differences are indicated in bold. Pseudo *R*-squared values are given for the total mixed model at level 1, i.e. within sessions. This measure is the proportion of reduction in variance of residuals. Note that this measure can also have negative values.

block 1 ($EMM_{block1} = 107.31$; $SE = 4.47$) compared to the remaining blocks ($EMM_{block2} = 116.79$; $SE = 4.47$; $EMM_{block3} = 121.37$; $SE = 4.47$; $EMM_{block4} = 122.39$; $SE = 4.48$). This increase in relative alpha power was not moderated by lighting condition ($F < 1$, ns). The interaction between lighting condition and measurement block was also not significant for the relative power in the theta and beta ranges (both $F < 1$, ns). This shows that the effect of illuminance on the relative theta power was not significantly modulated by time in session.

Time of day had no significant main effect on the relative theta and alpha power during the light exposure (both $F < 1$, ns), but the relative beta power differed significantly with time of day ($F(1,598) = 3.88$; $p = 0.05$): beta showed a higher increase relative to baseline in the afternoon ($EMM = 110.72$; $SE = 2.65$) than in the morning sessions ($EMM = 106.92$; $SE = 2.58$). The interaction between lighting condition and time of day did, however, have a significant effect on alpha ($F(1,572) = 4.26$; $p = 0.04$). *Post hoc* comparisons showed that alpha was higher in the 200 lx condition ($EMM = 122.19$; $SE = 4.55$) than in the 1000 lx ($EMM = 114.42$; $SE = 4.52$) in the morning ($p < 0.01$), but not in the afternoon sessions ($EMM_{200lx} = 115.08$, $SE = 4.70$; $EMM_{1000lx} = 116.17$, $SE = 4.68$; $p = 0.73$). This interaction effect was not moderated by cortical area ($F < 1$, ns). Neither of the interaction effects between lighting condition and time of day on theta and beta were significant nor was the three-way interaction with cortical area (all $p > 0.10$). This indicates that the effect of bright light exposure on theta was not significantly moderated by time of day.

Trait vitality was significantly related to the relative power in the theta range [$F(1,29) = 4.63$; $p = 0.04$), suggesting that participants with a higher trait vitality had a lower relative theta power during the light exposure ($B = -7.29$). A similar non-significant trend was found for the relative alpha power ($B = -10.25$; $F(1,31) = 3.55$; $p = 0.07$). Trait vitality was not significantly related to the relative power in the beta range ($F < 1$, ns). Chronotype, light sensitivity and global sleep quality were not significant predictors for the relative theta, alpha and beta power during the light exposure ($p > 0.05$).

4. Discussion

The current study explored the effect of bright light exposure on brain activity measured with EEG during daytime and under regular work conditions, which means that participants were not sleep-deprived nor exposed to very dim light during or before the experiment. Earlier reported results on the self-report, task performance, heart rate and skin conductance measures employed in the same study showed acute alerting effects of daytime exposure to the higher illuminance on participants' feelings, ability to sustain attention and autonomic nervous activity.[19,44] These results suggested that day-active persons feel less sleepy and more energetic, perform better on a sustained attention task and have a higher heart rate and skin conductance level when exposed to bright light as compared to commonly experienced illuminances during regular daytime office hours. In line with these results, the current findings on EEG showed that exposure to bright light (1000 lx vs. 200 lx at the eye) affected EEG power densities in the theta and alpha range during regular daytime hours. As expected, the relative power density in the theta range was lower when exposed to a higher illuminance as compared to a commonly experienced illuminance. In addition, the relative alpha power was lower in the 1000 lx versus 200 lx condition in the morning, but not in the afternoon sessions. Lighting condition had no significant effect on the relative power in the beta range.

The results of this paper are in line with earlier studies performed at night, which showed that bright light exposure results in

lower power in theta range (e.g. Cajochen *et al.*[10]). In addition, the results are in line with results showing that nocturnal exposure to blue (vs. green) light[52] or exposure to a higher CCT in the late evening[53] may – in addition to a lower sleepiness and faster responses on sustained attention tasks – result in lower theta power. Moreover, they corroborate the results of the study by Kaida *et al.*[34] performed during daytime, which reported a lower alpha power when exposed to natural light through a window. Our results, however, are in contrast with those reported by Badia *et al.*[8] and Daurat *et al.*[30] who found no significant effects of bright light exposure in the theta, alpha or beta range during daytime. Both studies, however, employed only a small number of participants ($N = 8$), and therefore the statistical power in these studies was relatively low. Note also that Lockley *et al.*[52] reported – in addition to a lower theta power – an increase in the higher alpha range (9.5–11 Hz) with eyes open during 6.5 hours of exposure to dim blue versus green light at night, while our study revealed both a lower theta and alpha power (in the morning) under brighter light during daytime. A recent laboratory study by Rahman *et al.*[36] studied the effect of a similar light manipulation as employed by Lockley *et al.*[52] on the awake EEG during the subjective day after prior exposure to very dim light (<3 lx). Their results revealed a lower power density in the high theta/low alpha range (7.5–8.5 Hz), but no significant difference in the high alpha range (9–12 Hz) with eyes open under exposure to dim blue versus green light for 6.5 hours during daytime. Moreover, a recent laboratory study reported a lower alpha power under exposure to dim red as well as blue light (both at 40 lx) as compared to darkness (<0.01 lx) in the early morning.[54] In addition, Sahin and Figueiro revealed a lower power in both the theta and alpha range under exposure to dim red light as compared to darkness (<0.01 lx) in the afternoon.[37] A very recent study also reported lower power in the theta–alpha (5–9 Hz) and alpha range (8–12 Hz) under exposure to white light of 360 lx as compared to very dim light (<5 lx) during daytime around midday and in the late afternoon.[55]

Earlier studies investigating the relationship between the awake EEG power density and alertness have reported a negative correlation between theta and subjective alertness during about 40 hours of sustained wakefulness,[20,28] during daytime after restricted sleep[23,24] and at night.[21] Alpha and alertness showed, however, a less consistent relationship in the literature: although studies measuring the awake EEG during about 40 hours of sustained wakefulness revealed a negative correlation between subjective sleepiness and the (high) alpha range,[20,28] alpha power was positively related to subjective sleepiness as well as to decrements in performance during nighttime and daytime after sleep deprivation.[21,23,24] In the current study, a lower power in the theta and alpha range was accompanied by a lower self-reported sleepiness, higher subjective vitality and better performance on a sustained attention task.[19]

In line with our earlier findings on the self-report measures and heart rate,[19] effects on the EEG were not dependent on the duration of the light exposure. This suggests that a higher illuminance can have an immediate activating effect on indicators for cortical arousal and autonomic nervous activity, as well as on the subjective experience of alertness and vitality. In a recent overview, Vandewalle *et al.* have suggested that exposure to light can modulate cortical activity as assessed with fMRI within 18 minutes of exposure.[56] The current data suggest that the onset of modulation in EEG power density can occur within two minutes of bright light exposure, as we see no moderation by time in session. In contrast, our earlier results showed that the effects on sustained attention and HRV were more

pronounced towards the end of the hour of light exposure, in other words, these indicators demonstrated a delayed effect of bright light exposure.[19] Together, these results suggest varying onsets of bright light effects with duration of exposure for the different types of measures for alertness and arousal. It should be noted that the light exposure in the current laboratory study was relatively brief (i.e. one hour), so we cannot predict whether the alerting and activating effects of daytime bright light exposure will persist – and perhaps will be stronger – with prolonged exposure. Future research should investigate the effects of prolonged exposure periods as well as potential after-effects during daytime.

The effect of lighting condition on the relative alpha power was more pronounced in the morning sessions. The earlier results had shown no time-dependent effect of daytime light exposure on subjective sleepiness and vitality and the indicators for autonomic nervous activity, but indicated that bright light effects on sustained attention were more pronounced in the morning.[19] A potential explanation for more pronounced effects in the morning is that participants' light history prior to the sessions – which was probably larger in the afternoon than in morning as participants reported spending more time outdoors before the afternoon sessions – may have affected their sensitivity to the light manipulation. In fact, several studies have provided indications that the acute activating effects of light are dependent on a person's prior light history.[57–61]

The current study showed that the effect of bright light on EEG power density in the theta range was moderated by cortical area, suggesting that this effect is location specific. Modulations in the relative theta power were most pronounced at the frontal lobe. Frontal theta power has been related to sleepiness[28] and sleep pressure,[62] which is also in line with the results on self-reported alertness and vitality under bright versus commonly experienced light reported previously.[19] Yet, the spatial resolution in the current study is too low to determine the exact brain mechanisms involved in the acute alerting effects of daytime light exposure. Photons reaching the human retina may activate different neural pathways through which light information is sent to brain areas involved in image-forming as well as non-image forming processes.[4,5,63] Research has shown that light can activate brain areas involved in vision, alertness, cognition, emotion and circadian regulation.[56,63,64] Due to different potential pathways and brain areas that can be activated by light simultaneously, we cannot determine the neural processes underlying the alerting effects found in our study. This would require more research among day-active persons employing a higher spatial resolution, for instance, by using fMRI.

As we compared only two illuminances during one hour of exposure, we cannot determine the optimal light dosage in terms of illuminance and duration. Note, for instance, that the 200 lx (at the eye) condition may have also induced alertness if compared to darkness or very dim light exposure. Nevertheless, the current study suggests that exposure to bright light for one hour can enhance alertness – as assessed with both subjective and objective indicators – during regular work hours as compared to commonly experienced levels. Exploring the daytime effects of a more varied range of illuminances and durations as well as spectral compositions on alertness will provide additional insights into persons' relative responsiveness to different illuminances, possible trade-offs between illuminance, duration and spectrum, and the minimum necessary light dosage to induce light responses. Moreover, exploration of a larger range of illuminances can provide more insights about potential non-linear relationships, as have been shown in earlier research at night (e.g. Cajochen *et al.*[10]).

5. Conclusion

Results showed an acute alerting effect of illuminance on the relative power density in the theta range and alpha range (in the morning), with lower power under bright light as compared to the commonly experienced light levels during regular daytime work hours. Together, the results on EEG and the earlier findings on subjective alertness and vitality and on objective indicators for task performance and autonomic nervous activity reported elsewhere[19] show that relatively brief exposure to a higher illuminance can also promote alertness during daytime, when melatonin levels are low, and in the absence of sleep restriction and light deprivation. Even though the current study provides new insights in potential acute activating effects of bright light exposure during daytime, more research is necessary to establish optimal lighting scenarios for daytime situations.

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