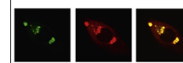


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Research Report

Bright illumination reduces parietal EEG alpha activity during a sustained attention task[☆]



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ABSTRACT

The influence of the illumination condition on our cognitive-performance seems to be more critical in the modern life, wherein, most people work in an office under a specific illumination condition. However, neurophysiological changes in a specific illumination state and their cognitive interpretation still remain unclear. Thereby, in the present study, the effect of different illumination conditions on the same cognitive performance was evaluated particularly by EEG wavelet analyses. During a sustained attention task, we observed that the higher illumination condition yielded significantly lower parietal tonic electroencephalogram (EEG) alpha activity before the presentation of the probe digit and longer reaction times, than that of the other illumination conditions. Although previous studies suggest that lower prestimulus EEG alpha activity is related to higher performance in an upcoming task, the reduced prestimulus alpha activity under higher illumination was associated with delayed reaction times in the present study. Presumably, the higher background illumination condition seems to be too bright for normal attentional processing and distracted participants' attention during a sustained attention task. Such a bottom-up effect by stimulus salience seemed to overwhelm a prestimulus top-down effect reflected in prestimulus alpha power during the bright background condition. This finding might imply a dynamic competition between prestimulus top-down and post-stimulus bottom-up processes. Our findings provide compelling evidence that the illumination condition substantially modulates our attentional processing. Further refinement of the illumination parameters and subsequent exploration of cognitive-modulation are necessary to facilitate our cognitive performance.

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1. Introduction

We experience that lighting conditions substantially influence on our daily physiological and psychological phenomena such as photobiological and cognitive processes (Boyce, 2006). The influence of the illumination condition on our work-performance seems to be more critical in the modern life, wherein, most people work in an office under a specific illumination condition, while blocking the natural sunlight. For example, the amount of mental loading under an indoor environment would be susceptible to the illumination condition that surrounds us. If any neurophysiological correlate of such illumination effect is revealed, it would provide substantial evidence that indicates the psychological effect of illumination. However, neurophysiological changes in a specific illumination state and their cognitive interpretation still remain unclear although there are several previous studies of the relationship between illumination and electroencephalogram (EEG) activity (Ermolaev and Kleinman, 1983; Kobrick and Cahoon, 1968; Maher et al., 2001; Noguchi and Sakaguchi, 1999; Osaka and Yamamoto, 1978; Robinson, 1966). Much of the existing literature on environmental illumination conditions and EEG focused on basic physiological states (e.g., alpha rhythm modulation by stimulus luminance (Kobrick and Cahoon, 1968; Robinson, 1966); lowering effect of physiological activity by illuminance and color-temperature (Noguchi and Sakaguchi, 1999)), and less has focused on cognitive processes.

Thereby, in the present study, the effect of different illumination conditions on the same cognitive performance was evaluated particularly by event-related potential (ERP) and EEG wavelet analyses. Various psychological impressions in humans are induced by different illuminance values and color-temperature (Noguchi and Sakaguchi, 1999). These two illumination parameters are widely recognized as essential factors in interior lighting (Nakamura and Karasawa, 1999); therefore, we investigated the effects of these two representative illumination dimensions on cognitive performance. The illuminance is a measure of the intensity of the incident light and the color-temperature of a light source is the absolute temperature of an ideal black-body radiator whose chromaticity most nearly resembles that of the light source. Among a variety of cognitive tasks, an attention task was chosen for the present study since attention is one of the most fundamental features involving our cognitive performance in daily life (Sohlberg and Mateer, 1989a, 1989b), and attentional deficits are associated with a variety of psychiatric disorders such as ADHD (attention-deficit/hyperactivity disorder) and schizophrenia (Carter et al., 2010). Attention deficits are a prominent cognitive dysfunction in ADHD and schizophrenia. For example, a sustained attention task is valuable for differentiating the schizophrenia spectrum disorder (Hagh-Shenas et al., 2002), and ADHD patients show greater frontal and parietal alpha EEG power (8–10 Hz) during a sustained attention task (Loo et al., 2009). Considering that bright light plays a therapeutic role in ADHD (Gruber et al., 2007) and schizophrenia (Aichhorn et al., 2007), lighting conditions seem to modulate human attentional processing. Therefore, it is important to understand how illumination

influences attentional processing and cognitive performance. Among the various aspects of attention, we selected sustained attention to assess under specific combinations of illumination parameters. We supposed that a stationary illumination condition might affect a sustained mental state, so sustained attention was considered to be one of the appropriate targets to investigate possible influences by background illumination. Sustained attention, the capability to maintain the focus of attention over time (Mirsky et al., 1991), can be generally assessed, using the continuous performance test (CPT; Riccio et al., 2001), which is featured by a rapid presentation of continuously changing stimuli with an infrequently occurring target stimulus.

Several studies have evaluated different aspects of EEG activity recorded during sustained attention tasks. Since ongoing tonic alpha activity has been reported to be associated with the sustained attention processing (Dockree et al., 2007; Orekhova et al., 2001), we focused on the analysis of EEG alpha activity related to sustained attention task-performance under different illumination conditions. Because lower prestimulus alpha power facilitates task-performance (Ergenoglu et al., 2004; Hanslmayr et al., 2007), we investigated whether background illumination conditions can affect the prestimulus alpha activity level, which reflects prestimulus preparatory mental states for the sustained and selective allocation of neural processing resources to target information. In particular, neural activity related to sustained attentional processing has been reported in the parietal brain region (Lee et al., 2013; Thakral and Slotnick, 2009). Therefore, we hypothesized that light conditions would modulate alpha activity in the parietal region during a sustained attention task. For example, it was suggested that parietal alpha synchronization reflects an active inhibition of certain parietal networks involved in maintaining attention to peripheral visual field (Orekhova et al., 2001), and that parietal alpha activity ipsilateral to the attended hemi-field was enhanced relative to the control condition when attention was shifted away from fixation (Cosmelli et al., 2011). Moreover, we hypothesized that the background illumination condition would affect selective sensory gain control in the visual pathways. Sensory gain control is defined as a change in neural excitability that occurs in the early perceptual analysis of visual properties (Wijers et al., 1997). In this view, the early ERP components are typically interpreted as evidence for such a sensory gain control process (Hillyard and Mangun, 1987). Indeed, the P1 and N1 components were identified as electrophysiological correlates of early attentional processing (Luck et al., 1990; Mangun and Hillyard, 1995). Because early ERP components are more susceptible to bottom-up properties and later ERP components are responsible for top-down processes (Skrandies, 1984; Zani and Proverbio, 1995), we examined both early (P1 and N1) and relatively late ERPs (P2 and N2) to determine whether light affected cognitive performance.

2. Results

We observed that the reaction times were significantly influenced by the illuminance factor ($F(1,20)=8.365, p<0.01$;

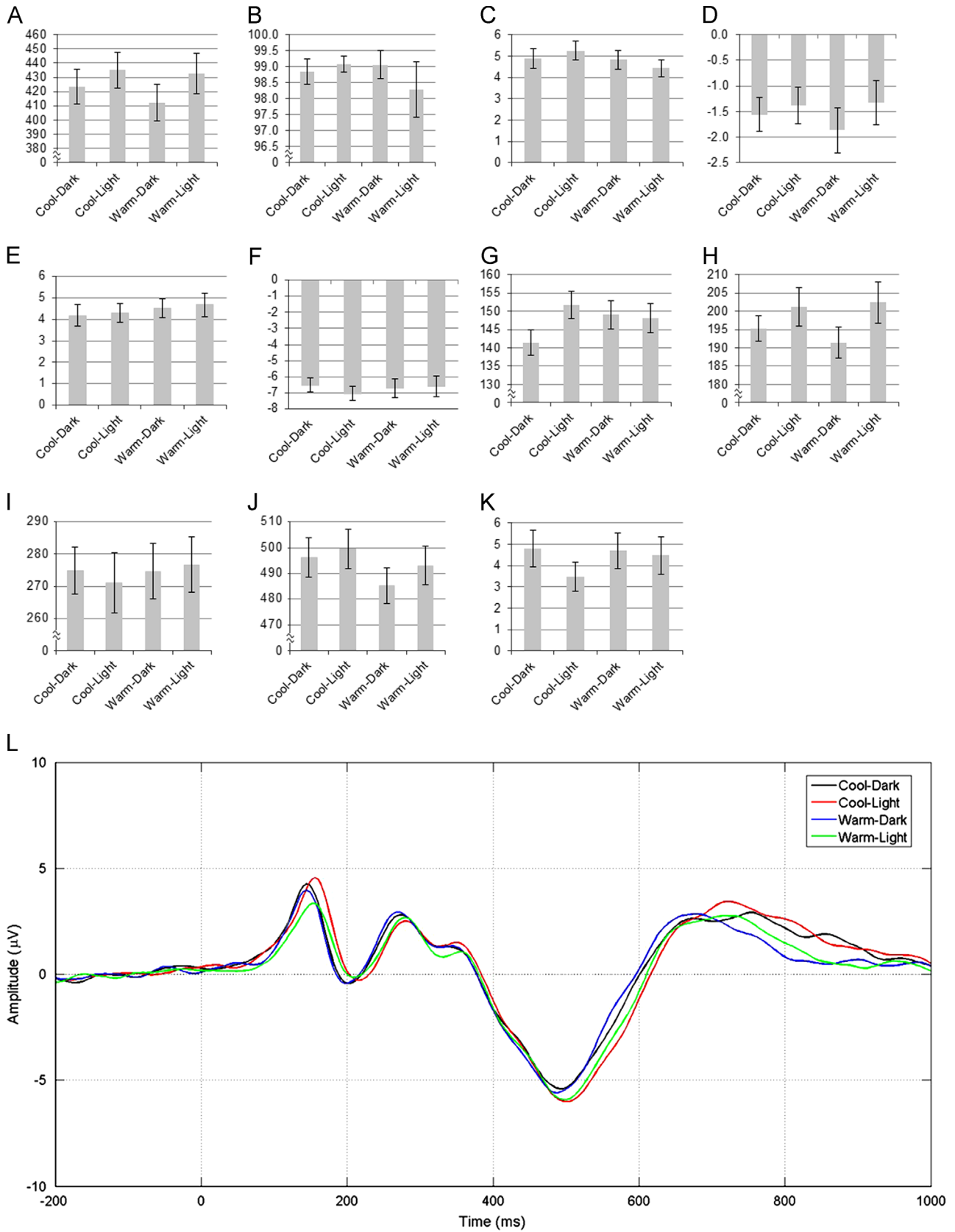


Fig. 1 – Effects of illumination conditions (cool-dark, cool-light, warm-dark, and warm-light) upon (A) reaction times, (B) accuracy of the task-performance, (C) P1 amplitude, (D) N1 amplitude, (E) P2 amplitude, (F) N2 amplitude, (G) P1 latency, (H) N1 latency, (I) P2 latency, (J) N2 latency, and (K) EEG alpha power. Means and standard errors are shown. (L) Grand-averaged ERPs at the electrode Pz (black line: cool-dark, red line: cool-light, blue line: warm-dark, and green line: warm-light).

Fig. 1), but not by the color-temperature ($F(1,20)=1.710$, $p=0.206$). It indicated that the bright condition (mean: 433.832 ms) led to significantly longer reaction times than the dark condition (mean: 417.643 ms). There was no significant interaction effect with regard to the reaction times ($F(1,20)=0.580$, $p=0.455$). Regarding the accuracy of task-performance, there were no significant main effects of the illuminance ($F(1,20)=2.993$, $p=0.099$) and color-temperature factors ($F(1,20)=0.646$, $p=0.431$) as well as no significant interaction effect ($F(1,20)=2.143$, $p=0.159$).

The P1 amplitude was not significantly influenced by the illuminance ($F(1,20)=0.540$, $p=0.471$) and color-temperature factors ($F(1,20)=1.037$, $p=0.321$). There was no significant interaction between these factors in regard to the P1 amplitude ($F(1,20)=0.394$, $p=0.537$). As for its latency, we found no significant main effects of the illuminance ($F(1,20)=2.410$, $p=0.136$) and color-temperature factors ($F(1,20)=0.565$, $p=0.461$). However, we observed a marginally significant interaction effect between these factors with regard to the P1 latency ($F(1,20)=3.859$, $p=0.064$). Although the N1 amplitude was not significantly modulated by the color-temperature factor ($F(1,20)=0.365$, $p=0.553$), the main effect by the illuminance factor almost reached the level of statistical significance ($F(1,20)=4.225$, $p=0.053$). The bright condition (mean: $-1.358 \mu\text{V}$) yielded more positive going N1 amplitudes than the dark condition (mean: $-1.713 \mu\text{V}$). No significant interaction effect was detected in the N1 amplitude ($F(1,20)=0.653$, $p=0.429$). We found no significant differences in the N1 latency by the color-temperature factor ($F(1,20)=0.395$, $p=0.537$), but the N1 latency was significantly influenced by the illuminance factor ($F(1,20)=7.897$, $p<0.05$). Their mean values indicated that high illuminance (201.75 ms) resulted in significantly longer N1 latencies, than low illuminance (193.35 ms). There was also a marginally significant interaction effect as well ($F(1,20)=3.440$, $p=0.078$).

The P2 amplitude was not significantly altered by the illuminance ($F(1,20)=0.361$, $p=0.555$) and color-temperature ($F(1,20)=2.134$, $p=0.160$), and we observed no significant interaction between these factors in regard to the P2 amplitude ($F(1,20)=0.009$, $p=0.926$). As for its latency, we found no significant main effects of the illuminance ($F(1,20)=0.031$, $p=0.861$) and color-temperature ($F(1,20)=0.226$, $p=0.639$). There was no significant interaction between these factors in regard to the P2 latency ($F(1,20)=0.377$, $p=0.546$). The N2 amplitude was not significantly modulated by the illuminance ($F(1,20)=0.927$, $p=0.347$) and color-temperature ($F(1,20)=0.119$, $p=0.734$). There was no significant interaction between these factors in regard to the N2 amplitude ($F(1,20)=2.532$, $p=0.127$). As for its latency, we observed no significant main effects of the illuminance ($F(1,20)=3.371$, $p=0.081$) and color-temperature ($F(1,20)=3.681$, $p=0.069$). There was no significant interaction between these factors in regard to the N2 latency ($F(1,20)=0.534$, $p=0.473$).

Furthermore, we observed a tonic alpha activity around the parietal region, during the sustained attention (Fig. 2), and the mean value of prestimulus parietal EEG alpha power was significantly modulated by the illuminance ($F(1,20)=16.300$, $p<0.005$; bright: $3.974 \mu\text{V}^2$, dark: $4.748 \mu\text{V}^2$) and color-temperature factors ($F(1,20)=4.727$, $p<0.05$; warm: $4.583 \mu\text{V}^2$, cool: $4.139 \mu\text{V}^2$). These effects in power were still valid without

adjustment for individual alpha frequency (IAF). These results imply that the higher condition may be more influential to yield significantly lower parietal EEG alpha power than the color-temperature condition. Although the parietal alpha activity was most reduced under the higher color-temperature and higher illumination condition (Figs. 1L and 2), there was no significant interaction between the color-temperature and the illuminance ($F(1,20)=2.610$, $p=0.122$).

3. Discussion

We found that both ERP components and EEG alpha activity were significantly modulated, depending on the illumination condition during the sustained attention task. Since we observed the illuminance affecting the early ERP component N1, the degree of brightness seems to be an influential factor in the early information processing, as compared with the color-temperature. Although previous studies proposed a significant relation between attention and P1/N1 components (Luck et al., 1990), at least under the present sustained attention task, we observed the dissociative modulation between P1 and N1 by the illumination factor. In addition, the late ERP components such as P2 and N2 showed no significant changes in relation to the background lighting conditions. Since the early ERP components are more influenced by bottom-up sensory factors than are the later ERP components, which reflect rather top-down cognitive processing (Skrandies, 1984; Zani and Proverbio, 1995), the illuminance appears to be much closer to a physical factor modulating our early visual processing. Meanwhile, we did not observe any significant modulation of the P1 component by the illumination conditions, this quite early ERP component does not seem to be so susceptible to the external lightning conditions than the N1 component.

Based on the observations of prestimulus alpha activity during the sustained attention period, it is likely that both illuminance and color-temperature substantially influenced participants' mental states preparing for the upcoming stimuli. Although the 2-sec constant inter-stimulus interval (ISI) used in the present study might contribute to both shorter reaction times and changes in prestimulus alpha activity reflecting temporal anticipation (Klimesch, 2012; Min et al., 2008), our observation of a significant difference in both reaction times and prestimulus alpha power seems to be attributed to the different lighting conditions rather than the degree of temporal anticipation. This is because significant differences in both reaction times and prestimulus alpha power were detected under the different lighting conditions, which used the same constant ISI. Based on the 2-D scalp distribution (Fig. 2A), the 3-D source distribution generated by sLORETA (Fig. 2B) may provide a more reliable estimation of the location of neural generators, which is likely the parietal region. Tonic parietal EEG alpha activity reflects ongoing, sustained attention (Dockree et al., 2007), and such patterns of tonic alpha activity can reveal the cognitive resources available to an individual (Klimesch, 1999). Moreover, alpha activity is considered to reflect "anticipatory attention" or "attentional buffer" (Klimesch, 2012). Klimesch (2012) suggested that alpha activity may reflect an attentional buffer

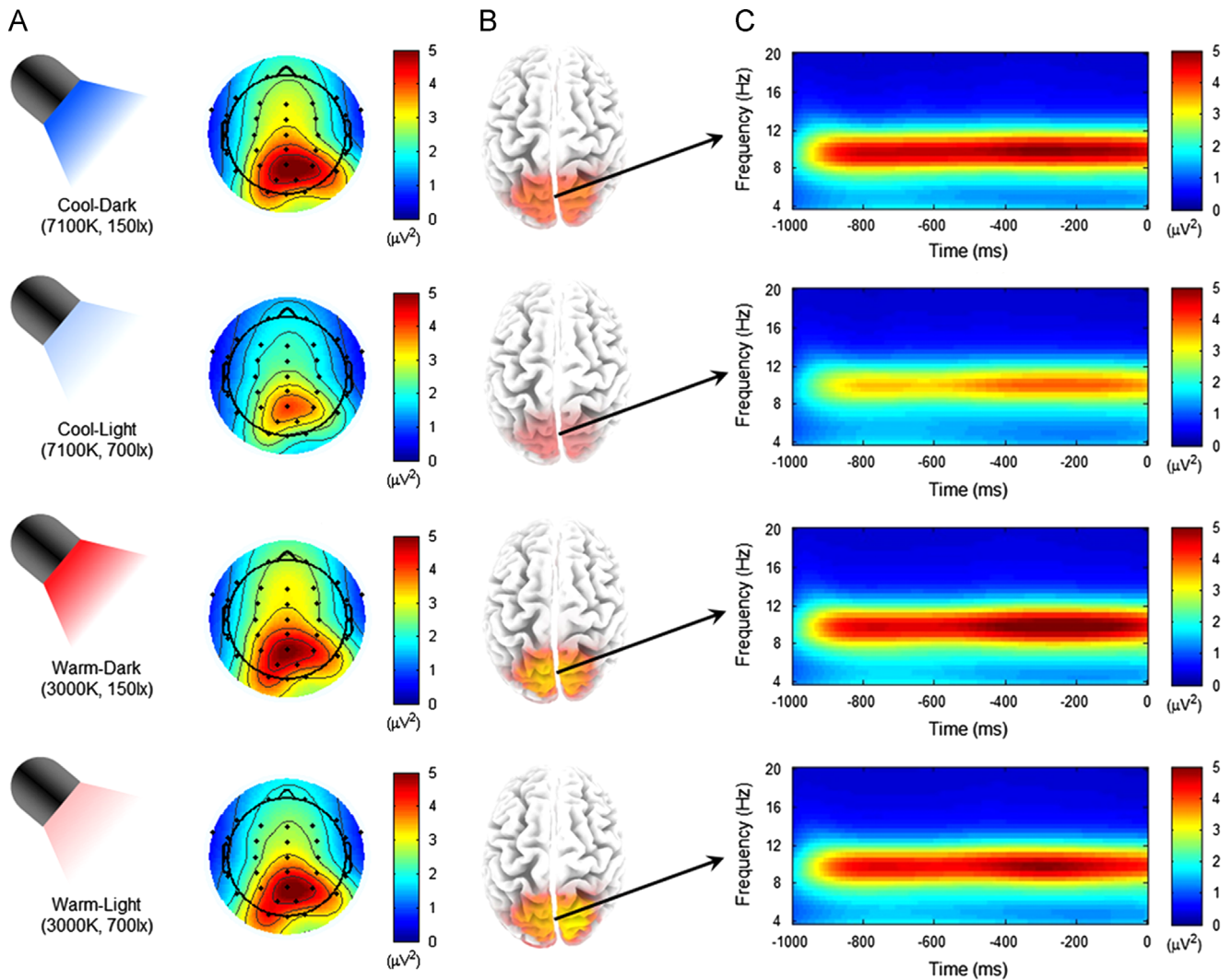


Fig. 2 – (A) Two-dimensional scalp distribution (top-view), (B) three-dimensional scalp distributions by sLORETA (top-view) and (C) its time-frequency representation of the electrode Pz with respect to the 4 illumination conditions.

that maintains target information, and the ability to activate the attentional buffer might selectively lead to a pronounced anticipatory event-related desynchronization (ERD) of alpha activity in the fore-period of the rapid serial visual presentation paradigm. Although our current experimental paradigm was not presented rapidly, this conception may provide a plausible explanation for our finding that bright light induced a pronounced anticipatory ERD of alpha activity. That is, bright background light may facilitate the temporal anticipation of a stimulus, which was reflected by reduced prestimulus alpha power in the present study.

It is noteworthy that we observed reduced prestimulus alpha power accompanied by delayed reaction times under the bright background light. Since the attention decrement is analogous to an increment of reaction time (Cohen and O'Donnell, 1993), the observed delay in reaction times may imply a possible disturbance of normal attentional processing by high illuminance. As we observed no significant differences in the accuracy of participants' performance, the lighting conditions used in the present study may not have been strong enough to influence the entire performance stage

of behavioral processing. Because our observations appear to contradict previous studies that showed lower prestimulus alpha activity yields higher task-performance (Ergenoglu et al., 2004; Hanslmayr et al., 2007), it is possible that lower prestimulus alpha activity does not always yield higher task-performance. For instance, if salience of a certain stimulus-feature is strong enough to consistently influence information processing, it is likely that a level of prestimulus alpha activity does not predict the quality of poststimulus task-performance. That is, although lower alpha activity was observed prior to the stimulus onset under the bright condition, it might fail to induce higher task-performance presumably due to the salience of the brighter background condition, which might interrupt the sustained attention task-performance.

Presumably, a difference in the luminance contrast for stimulus-perception might yield an overwhelming salience of stimulus-feature. Indeed, the luminance of the bright background was 4.4 times higher than that of the dark background; thus, attentional processing of the stimuli might have been interfered with such higher luminance backgrounds. This

interpretation seems to be plausible because the bright condition used in the present study (700lx) was much brighter than the normal illuminance for comfortable working conditions (approximately 500lx; Boyce, 2006). Therefore, the bright light might have distracted participants and interrupted their normal inhibitory control in attentional processing during a cognitive task. Presumably, the overbright background light used in the present study might have enhanced the participants' arousal beyond an optimal level. That is, at very high arousal levels, attention may boost responses to stimulus input, but not in an effective or focused manner. Attention generally refers to the selective allocation of neural processing resources to target information, at any level of arousal; whereas arousal is a state of the brain. The relationship between arousal and the ability to focus attention effectively is not linear; rather, arousal and attentional effectiveness are roughly related as an inverted U-shaped function, with low and high arousal levels with ineffective attention (Purves et al., 2008). For example, highly aroused people are too hyper to effectively focus their attention. Therefore, higher levels of illuminance in the room might interrupt temporal coupling in the alpha band within the prominent attention-related network, which may subsequently lead to prolonged reaction times. Presumably, lower prestimulus alpha reflects a preparatory mental state for an upcoming task and does not always indicate higher poststimulus task-performance. Although prestimulus alpha power dominantly reflects a prestimulus top-down state, a bottom-up effect by a stimulus salience seemed to overwhelm a prestimulus top-down effect during the bright background condition. This might imply an antagonistic competition between prestimulus top-down and poststimulus bottom-up processes. In other words, this discrepancy may be due to the impact ratio between top-down and bottom-up processing.

Alternatively, we may have a different explanation for the discrepancies between the results of previous studies and our observations. As mentioned in the Section 1, there might be light-induced changes in neural excitability involved in the early perceptual analysis of visual properties (i.e., sensory gain control), because we observed that an early ERP such as N1 (an electrophysiological correlate of early attentional processing) as well as delayed reaction times were significantly modulated by the level of background illuminance. This explanation is based on our observation that the level of background illuminance significantly affected the early N1 ERP (an electrophysiological correlate of an early attentional processing) and the delayed reaction times. The illuminance-induced changes in reaction time may be attributed to the physiological and dynamic aspects of the visual pathway to the motor cortex, which plays a major role in determining reaction times (Robinson, 1966). Such a bright light presumably generates an abnormal time delay from the retina to the motor cortex during button pressing since the photoreceptors in the retina behave in a light-dependent delayed manner (Pepperberg et al., 1992). Taken together, it seems that the background light might serve as a salient bottom-up or physically-driven feature, which might competitively interact with prestimulus top-down states.

Some of the previous studies examining luminance and EEG activity focus on the luminance of the stimulus, rather than the luminance of the background light (Johannes et al., 1995; Kobrick and Cahoon, 1968; Osaka and Yamamoto, 1978; Yoto et al., 2007).

Therefore, it is difficult to compare the results of those studies with our results in the present study. For instance, Johannes et al. (1995) observed that P1 and N1 amplitudes were increased when the stimulus luminance increased; whereas we observed N1 amplitude decreased when background light luminance increased. Despite this difference, EEG activity was modulated by the luminance of both the stimulus and the background. Yoto et al. (2007) found significant modulation of EEG alpha power when participants viewed A2-sized colored paper; whereas we observed color changes in the background light modulated EEG alpha power. However, they observed this effect over the fronto-central region, whereas we observed this effect over the parietal region. Such a discrepancy might be because they manipulated stimulus-color and we manipulated background-color. Therefore, a direct relationship between EEG alpha and luminance cannot be confirmed on the basis of these few studies; further studies are needed to confirm such a relationship. Similar to our experiment, Maher et al. (2001) modulated background illumination while recording EEG activity in human subjects. In that study, however, they analyzed another type of EEG alpha synchronization (the temporal response of the occipital alpha wave), so their results cannot be directly compared to ours. In accordance with our observations of N100, Ermolaev and Kleinman (1983) found an inverse relationship between background illumination and N130 amplitude. Moreover, consistent with our observations, Noguchi and Sakaguchi (1999) observed significant changes in alpha power with changes in color-temperature.

In summary, our findings provide compelling evidence that the illumination condition substantially influences our attentional processing which was reflected in the significant modulations of EEG activity. Further studies on illumination parameter-dependent efficacy of the cognitive performance and selection of the effective illumination parameters are necessary to develop appropriate applications to enhance the efficacy of our work-performance. For instance, such an illumination-mediated application to inefficient or impaired cognitive performance for probing its potential utility in the enhancement of work efficacy constitutes one of our future subjects of investigation.

4. Experimental procedure

4.1. Participants

EEG was recorded from all 23 neurologically normal participants (11 females; mean age 23; age range 19–31 years) in this study in accordance with the ethics guidelines established by the Institutional Review Board of Yonsei University and the Declaration of Helsinki (World Medical Association, 1964; 2002). Participants provided informed consent prior to the start of the experiment. All had normal or corrected-to-normal vision.

4.2. Procedure

We used a 60 × 60 cm² plate as the illumination source, which had 14 × 14 light-emitting diode (LED) arrays installed inside; this source was placed just above and behind the participant with a tilt angle of 10° to the vertical line as shown in Fig. 3A. A controller (WE7000, Yokogawa, Japan) could regulate the

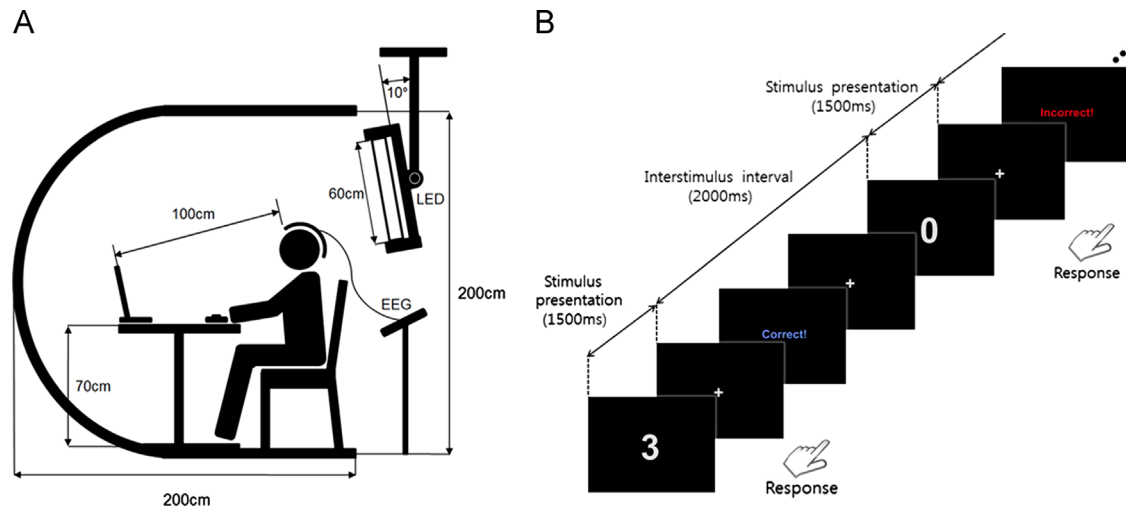


Fig. 3 – (A) A schematic diagram of the experimental setup within a Ganzfeld-dome and (B) a task flow diagram of the sample stimuli. Stimulus presentation was followed by a fixation cross presented during every inter-stimulus interval (ISI).

illuminance and color-temperature of the LEDs. To make the illumination as homogenous as possible all around the participant, the present experiment was performed within a capsule-shaped light-reflecting structure (Fig. 3A) called the “Ganzfeld-dome,” with an optical geometry with a 2-m diameter. Four different illumination conditions were provided with a factorial design of 2 color-temperatures (3000 K and 7100 K) by 2 illuminance levels (150lx and 700lx). This resulted in (1) the cool-dark (7100 K and 150lx), (2) the cool-light (7100 K and 700lx), (3) the warm-dark (3000 K and 150lx), and (4) the warm-light (3000 K and 700lx) conditions. Higher color-temperatures lead to bluish light, which we feel is a cool illumination condition; whereas lower color-temperatures produce yellowish or reddish light, which we feel is a warm illumination condition. These specific illumination parameters were chosen on the basis of the Kruithof curve (Kruithof, 1941), taking the technical limitation of the illumination device into consideration. Both comfortable and uncomfortable combinations of illuminance and color-temperature parameters have been described in the Kruithof curve. The order of illumination conditions was also counter-balanced across participants. Between illumination conditions, a 3-min dark break was provided to avoid a possible carry-over effect from one illumination condition to another. The optical parameters were measured on the display monitor by a chromameter (CL-200A, Konica-Minolta, Japan).

Although over 100 different versions of CPT could be in use (Greenberg and Waldman, 1993), participants in the present study were instructed to respond by pressing a button with one hand whenever the digit “0” appeared, which was the target stimulus. Furthermore, they were instructed to press a button with the opposite hand if one of the remaining single digits (1–9) was presented. A single-digit number randomly drawn from a series of single digits (0–9) was presented (one at a time) on the display monitor for 1500 ms with a 2000 ms ISI. The number “0” was a target stimulus, with an appearance frequency of 30%. The remaining 70% of stimuli was filled up with one of numerals from 1 to 9. Using a presentation-software (E-prime 2.0 Professional, Psychology Software Tools, USA), the target stimulus “0”

was presented 90 times, and the non-target stimuli (1 to 9) were shown 210 times in the entire experiment. The stimulus-digit in gray (luminance: 30.55 cd/m²) subtended at 4° (visual angle) and was presented in a black background monitor (luminance: 0.93 cd/m²), most of which was covered with a white paper except the area for the stimulus presentation to remove any reflections on the monitor. The luminance contrast of the stimulus against the dark background illumination (luminance: 38.26 cd/m²) was 1/1.25; whereas that of the light background illumination (luminance: 169.9 cd/m²) was 1/5.56. Participants were required to press a button as quickly as possible. Response hands were counterbalanced across participants. In order to enhance participants' motivation for efficient task-performance, feedback results for task-performance (i.e., correct or incorrect) was presented automatically after each stimulus (Fig. 3B). During the CPT performance, EEG was measured, using a NuAmp amplifier (Neuroscan, USA) with 40 Ag/AgCl electrodes, the location of which was in accordance with the international 10–10 system. An electrode on each mastoid was placed for the linked reference, and a ground electrode at AFz. Eye movement activity was monitored with two pairs of electrodes placed, both vertically and horizontally, with respect to both eyes. Electrode impedances were maintained below 5 kΩ prior to data acquisition. EEG was sampled at 250 Hz (analog band-pass filter 0.1–100 Hz). Data were epoched from 1000 ms prestimulus to 1000 ms poststimulus. Epochs containing eye-movements or other artifacts (maximum amplitude $\pm 100 \mu\text{V}$ or electrode drifts) were rejected. As a result, the average rejection rate was 10.27%. Only trials with correct responses were further analyzed. To avoid a confounding effect by targeting, the trials only for non-target stimuli were assessed to compare the effects across four different illumination conditions. Two participants had to be excluded from further analyses because of poor data quality.

4.3. Data analysis

Reaction times and accuracy of task-performance were measured for the behavioral analysis. Reaction times were collected within their individual 95% confidence interval.

The power of oscillatory activity was investigated by convolving the EEG signals with Morlet wavelets (Herrmann et al., 2005). The wavelet transform was performed for each individual trial, and the absolute values of the resulting transforms were averaged. This measure of signal amplitude in single trials reflects the total activity for a certain frequency range. In the present study, we computed the power (μV^2) of oscillatory activity. We confined the alpha activity to the frequency range from 8 to 12 Hz. Since it has been demonstrated that participants differ considerably in their “IAF” (Klimesch, 1999), the frequencies used in the wavelet analyses of alpha activity were determined individually for every participant. We employed a wavelet family with 7 as its constant ratio (Tallon-Baudry et al., 1997). In the case of 10 Hz, this yields a wavelet duration of 222.8 ms and a spectral bandwidth of 2.9 Hz around its central frequency. In the present study, the mental state of sustained attention, before the onset of the probe digit, was the main target to analyze. We principally focused on assessing EEG signals particularly in the period prior to the presentation of the probe digit. In such a prestimulus period, there was no stimulus-locked or event-related activity, so we conducted a frequency analysis, rather than an evoked potential analysis, in the prestimulus period. However, we performed additional event-related potential (ERP) analysis during the poststimulus period. For the total alpha activity, we computed the mean power in the time window from 800 to 200 ms prior to stimulus onset in each frequency range. This time window was chosen to avoid the temporal smearing of poststimulus activity into the prestimulus period. Within this time window, IAFs were obtained from the frequencies showing maximal power of each task in the alpha band on the electrodes P3, Pz, and P4. The range of the IAF across the participants was 8–12 Hz. No baseline correction was applied to the total alpha power, since the total alpha power in a prestimulus period would vanish after a baseline correction. Since the prestimulus alpha power was most pronounced around the parietal region during the sustained attention period (Fig. 2), we selected three electrodes representing parietal brain areas (i.e., P3, Pz, and P4) for further analysis. To make 3-D scalp distributions, as shown in Fig. 2B, source-localization software (sLORETA, version 20081104, The KEY Institute for Brain-Mind Research, Switzerland) was employed in the present study (Lehmann et al., 2012; Pascual-Marqui, 2002). sLORETA is one method that estimates the electric neural generators and computes images of neural activity from EEG data. Using the sLORETA, we performed a current density analysis in the 3-D Talairach/MNI space of the scalp-recorded electrical activity (Fuchs et al., 2002). The MNI brain volume was scanned at a spatial resolution of 5 mm, and this produced 6239 cortical gray matter voxels (Mazziotta et al., 2001). We calculated sLORETA images for prestimulus alpha power in the time frame from 800 to 200 ms prior to stimulus onset.

The amplitude and latency of the P1, N1, P2 and N2 components were also evaluated. For the ERP analysis, we performed a baseline correction from 200 ms prestimulus to stimulus onset, and assessed the maximum amplitude and latency of the P1, within the time window from 100 to 200 ms poststimulus, and the minimum amplitude and latency of the N1 within the time window from 150 to 250 ms

poststimulus. We also evaluated the maximum amplitude and latency of the P2, within the time window from 200 to 40 ms poststimulus, and the minimum amplitude and latency of the N2 within the time window from 400 to 600 ms poststimulus. All of these time windows were selected on the basis of their grand-averages and individual variances. These measures were also assessed on the same three parietal electrodes P3, Pz and P4. The averaged values across these three electrodes were used for the statistical assessment. All measures were analyzed with a repeated measures analysis of variance (ANOVA), which included two within-subjects factors labeled as “illumination” (bright vs. dark) and “color-temperature” (warm vs. cool). We used the Greenhouse–Geisser correction where appropriate.

Authors' contributions

BKM carried out the experiment, conducted the data analysis and prepared the manuscript. YCJ, EK, and JYP participated in the design of the study and helped to draft the manuscript. All the authors have read and approved the final manuscript.

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