

ILLUMINATION INFLUENCES WORKING MEMORY: AN EEG STUDY

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Abstract—Illumination conditions appear to influence working efficacy in everyday life. In the present study, we obtained electroencephalogram (EEG) correlates of working-memory load, and investigated how these waveforms are modulated by illumination conditions. We hypothesized that illumination conditions may affect cognitive performance. We designed an EEG study to monitor and record participants' EEG during the Sternberg working memory task under four different illumination conditions. Illumination conditions were generated with a factorial design of two color-temperatures (3000 and 7100 K) by two illuminance levels (150 and 700 lx). During a working memory task, we observed that high illuminance led to significantly lower frontal EEG theta activity than did low illuminance. These differences persisted despite no significant difference in task performance between illumination conditions. We found that the latency of an early event-related potential component, such as N1, was significantly modulated by the illumination condition. The fact that the illumination condition affects brain activity but not behavioral performance suggests that the lighting conditions used in the present study did not influence the performance stage of behavioral processing. Nevertheless, our findings provide objective evidence that illumination conditions modulate brain activ-

ity. Further studies are necessary to refine the optimal lighting parameters for facilitating working memory.
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Key words: working memory; frontal EEG theta activity; color-temperature; illuminance; Sternberg task.

INTRODUCTION

Our surrounding conditions, such as the illumination or layout of a workspace, can influence our work performance. Particularly in modern life, people are surrounded by artificial illumination. Different lighting conditions substantially influence a variety of our daily physiological and psychological mechanisms, including photobiological and cognitive processes (Boyce, 2006). Illumination is essential for humans because it allows us to accurately process visual stimuli. Different illumination conditions may alter the extent and accuracy of visual perception, thus affecting task performance. The main purpose of artificial illumination is to ensure that people can perform the given work in a comfortable, easy, and quick manner (Boyce, 2006). Insufficient light or uncomfortable light can lead to poor task performance by changing motivation, even if the light does not affect the property of stimuli (Boyce, 2006). Therefore, it is important to understand how illumination influences visual perception and cognitive performance.

Despite all that we know about the spectral properties of rod and cone photoreceptors in the retina, it is still unclear how much illumination conditions alter cognitive performance. Previous electroencephalogram (EEG) studies have investigated visual stimulus properties such as visual size (Busch et al., 2004, 2006), luminance contrast (Johannes et al., 1995; Shieh and Chen, 2005; Mathes and Fahle, 2007), and chromatic contrast (Momose, 2005; Mathes and Fahle, 2007; Boon et al., 2011). However, the effects of background illumination have received comparatively less attention. The influence of stimulus background illumination seems to be another variable that influences visual perception, cognitive processing, and behavioral responses. For instance, different values of illuminance and color-temperature yield various psychological impressions in humans (Noguchi and Sakaguchi, 1999). These two illumination parameters (i.e., illuminance and color-temperature) are widely recognized as essential factors in interior lighting (Nakamura and Karasawa, 1999). Illuminance is a measure of light intensity, while color-temperature refers to the absolute temperature of an ideal black-body radiator whose chromaticity most

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† These authors contributed equally to this work as the first authors. Abbreviations: ACC, anterior cingulate cortex; ANOVA, analysis of variance; EEG, electroencephalogram; ERP, event-related potential; LED, light-emitting diode.

nearly resembles that of the light source. A study by [Kruithof \(1941\)](#) on such psychological interactive effects of illuminance and color-temperature provides a curve delineating the psychologically pleasing or comfortable range for these parameters.

Despite numerous previous studies ([Robinson, 1966](#); [Kobrick and Cahoon, 1968](#); [Osaka and Yamamoto, 1978](#); [Ermolaev and Kleinman, 1983](#); [Noguchi and Sakaguchi, 1999](#); [Maher et al., 2001](#)), the neurophysiological correlates of different illumination conditions and their psychological effects remain unclear. Therefore, in the present study, we investigated the effect of illumination conditions on mental working efficacy using EEG. Since working memory is a fundamental feature of cognitive performance in daily life, we obtained EEG correlates of working-memory load, which is possibly modulated by illumination conditions that vary with both illuminance and color-temperature. Working memory is considered as an outcome of the capability to control attention on a particular mental representation in the presence of distracting influences ([Engle et al., 1999](#)). It is noteworthy that theta band activity is associated with working memory tasks ([Klimesch, 1999](#)). Theta activity increases when working memory is required, is sustained throughout the maintenance period, and then decreases when working memory is no longer required ([Raghavachari et al., 2006](#)). In particular, frontal midline theta activity is observed in humans performing working memory tasks ([Gevins et al., 1997](#); [Lazarev, 1998](#); [Ishii et al., 1999](#); [Jensen and Tesche, 2002](#)). Although frontal midline theta activity might be associated with hippocampal theta activity, depth recordings in the human brain indicate that cortical EEG and hippocampal theta activities are not always phase coupled at rest ([Kahana et al., 2001](#); [Cantero et al., 2003](#)). Rather, the anterior cingulate cortex (ACC) is considered the origin of frontal midline theta activity ([Gevins et al., 1997](#); [Ishii et al., 1999](#); [Onton et al., 2005](#)). Considering that frontal theta activity systematically increases with increasing working-memory load ([Gevins et al., 1997](#); [Krause et al., 2000](#); [Jensen and Tesche, 2002](#); [Onton et al., 2005](#)), task difficulty ([Lazarev, 1998](#); [Kahana et al., 1999](#)), and sustained attention ([Sauseng et al., 2007](#)), we focused our analysis on the relationship between frontal theta activity and working memory under different illumination conditions.

Of particular interest is the observation that theta activity can be involved in the [Sternberg \(1966\)](#) working memory task ([Raghavachari et al., 2001](#)). The Sternberg task, which is a classical test of working memory, is well suited for investigating the prestimulus theta activity related to working-memory load because each trial has a well-defined retention period over which participants must maintain the items presented during the encoding phase. We used the Sternberg task to evaluate working memory performance in the present study. In addition, early event-related potential (ERP) components such as P1 and N1 are known to be more susceptible to sensory factors than are the later cognitive ERP components ([Skrandies, 1984](#); [Zani and Proverbio, 1995](#)). Since the illumination condition may

serve as a bottom-up factor, the P1 and N1 ERP components were also assessed. Moreover, we hypothesized that the background illumination condition might influence selective sensory gain control in the visual pathways. Within the present context, sensory gain control is defined as an alteration in the neural excitability engaged 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 have been identified as electrophysiological correlates of an early attentional processing ([Luck et al., 1990](#); [Mangun and Hillyard, 1995](#)). Furthermore, spatial attention and stimulus luminance have been observed to interact in their effects on reaction times ([Hawkins et al., 1988](#); [Johannes et al., 1995](#)), and spatial attention has been studied in terms of early ERPs such as P1 and N1 ([Mangun et al., 1997](#); [Wijers et al., 1997](#)). In the present study, we investigated early ERP components with regard to their possible modulation by the background illumination condition. Specifically, we investigated the illumination effect on the maintenance period of working memory by exploring theta activity, and the bottom-up influence of illumination context on early visual responses by examining ERPs evoked with probe presentation.

EXPERIMENTAL PROCEDURES

Participants

EEG was recorded from all 22 normal participants (11 females; mean age 23) 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). Participants provided written informed consent prior to the start of the experiment. All had normal or corrected-to-normal vision.

Material and procedure

We used a 60 × 60 cm² plate as the illumination source, which had 14 × 14 light-emitting diode (LED) arrays installed inside. A controller (WE7000, Yokogawa, Japan) regulated the 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 called the “Ganzfeld dome” (cf. [Fig. 1](#)). For the illumination factors in the present study, we used two representative illumination dimensions: illuminance and color-temperature. Four different illumination conditions were provided with a factorial design of two color-temperatures (3000 and 7100 K) by two illuminance levels (150 and 700 lx). This resulted in (1) the cool–dark (7100 K and 150 lx), (2) the cool–bright (7100 K and 700 lx), (3) the warm–dark (3000 K and 150 lx), and (4) the warm–bright (3000 K and 700 lx) conditions (cf. [Fig. 3](#)). These specific illumination parameters were chosen on the basis of the [Kruithof](#)

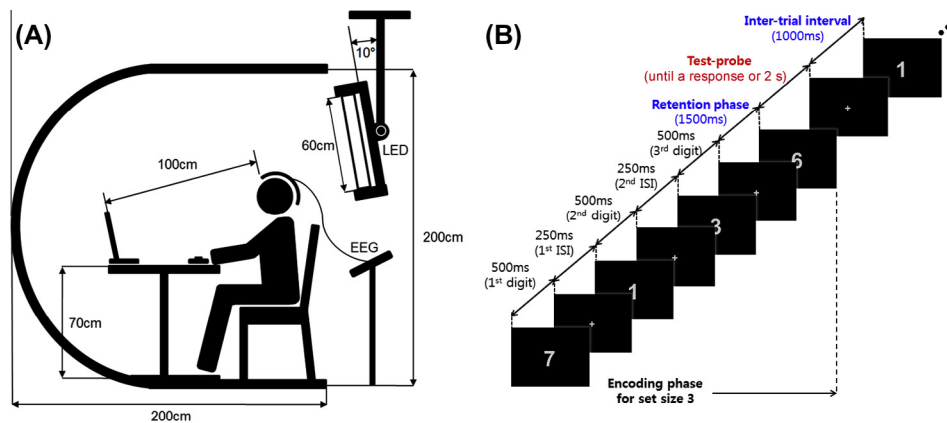


Fig. 1. (A) A schematic diagram of the experimental setup within a Ganzfeld-dome and (B) a task flow diagram of sample stimuli for the set size 3. Stimulus presentation was followed by a fixation cross presented during every inter-stimulus interval (ISI). The probe was presented until the participant responded or 2 s elapsed (the maximum response window). The inter-trial interval was 1 s, which began with the probe offset and ended with the onset of the next trial.

curve (Kruithof, 1941; Nakamura and Karasawa, 1999). The optical parameters were measured on the display monitor by a chromameter (CL-200A, Konica-Minolta, Japan). Between illumination conditions, a 3-min dark break was provided to avoid a possible carry-over effect.

Participants were presented with a memory set varying in set size. They were subsequently presented with a single digit “probe” after a 1500-ms retention period. Three types of memory sets consisting of 3, 5, and 7 digits randomly drawn from a series of single digits (0–9) were used during the Sternberg memory task. For example, in the Sternberg task with a 3-digit memory set, three numerals randomly drawn from a series of single digits (0–9) were visually presented (one at a time) consecutively on the display monitor for 500 ms with an inter-stimulus interval of 250 ms (cf. Fig. 1B). After this encoding phase, a 1500-ms retention period was given before the probe-test phase, in which the participants had to respond to decide whether the probe digit was part of the memory set presented during the encoding phase. The same procedure was applied to both 5-digit and 7-digit memory sets, except for the number of presented single digits (5 and 7 digits, respectively) during the encoding phase. Three types of memory sets were presented at random and equally often to each participant. The gray-colored digits (30.55 cd/m^2) were presented in a black background (0.93 cd/m^2 ; Weber contrast = 31.85). The stimulus-digit was subtended at 4° (visual angle) and was presented using a presentation software (E-prime 2.0 Professional, Psychology Software Tools, Sharpsburg, PA, USA), which enabled us to present the digit stimulus randomly. The probe was presented until the participant responded or 2 s elapsed (the maximum response window). The inter-trial interval was 1 s, which began with the probe offset and ended with the onset of the next trial. Each participant performed 60 trials for each memory set type, in each illumination condition. Three blocks (3 memory set sizes under one illumination condition) constituted each session, which included 180 trials (3 memory set sizes \times 60 trials). A typical session for each illumination condition took

approximately 20 min. The participants were required to press a button as quickly as possible. Response hands were counterbalanced across participants. During the Sternberg task performance, EEG was measured using a NuAmp amplifier (Neuroscan, Charlotte, NC, USA) with 32 Ag/AgCl electrodes, the location of which was in accordance with the international 10-10 system. An electrode was placed on each mastoid as a linked reference, and a ground electrode was placed at AFz. Eye movement activity was monitored with two pairs of electrodes placed both vertically and horizontally with respect to both eyes. 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 16.7%. Electrode impedances were maintained below $5 \text{ k}\Omega$ prior to data acquisition. EEG data were sampled at 250 Hz (analog band-pass filter 0.1–100 Hz).

Data analysis

Reaction times and accuracy of task performance were measured for behavioral analysis. Reaction times were collected within their individual 95% confidence interval. EEG data were epoched from 1000 ms prestimulus to 1000 ms poststimulus intervals. Only trials with correct responses were further analyzed. Two participants had to be excluded from analysis because of poor data quality, thus EEG data from 20 participants were analyzed. We measured the ERP components for the occipital P1 (maximum peak from 100 to 180 ms poststimulus) and N1 (minimum peak from 160 to 240 ms poststimulus) averaged across three occipital electrodes (i.e., O1, Oz, and O2) where the early bottom-up processing was most expected. We performed a baseline correction from 200 ms prestimulus to stimulus onset on the ERPs. We also analyzed EEG theta activity (4–8 Hz) that was averaged across the three frontal electrodes (i.e., Fp1, Fz, and Fp2) where theta power was most pronounced during the retention period. All of these time windows were selected on the basis of their grand-averages and

individual variances. In general, the peak frequencies within the theta band varied between participants, so the peak frequencies used in the wavelet analyses of theta activity were determined individually for each participant. 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, using Matlab (ver. R2011b, The MathWorks). This measure of signal amplitude in single trials reflects the total activity for a certain frequency range.

In the present study, we also computed the power (μV^2) of oscillatory activity. For recording the total theta activity, we computed the mean power in the time window from 800 to 200 ms prior to the onset of the probe stimulus. The time 0 was defined as the onset of the probe stimulus in the testing phase. This time window was chosen to avoid the temporal smearing of poststimulus activity into the baseline (an artifact of wavelet transformation). The wavelet transformation considers multiple time points around the respective time point for convolution, and thus the peak width of the convolved signal is smeared into the baseline. Accordingly, the time window for calculating the baseline should be chosen to fairly precede the stimulus onset. For example, a 5-Hz wavelet of theta activity has a 200-ms wavelength, so the period prior to approximately 200 ms before the stimulus onset should be chosen for the baseline. All measures were analyzed using a repeated measures analysis of variance (ANOVA) that included two within-subject factors labeled as “illumination condition” and “working-memory load (the size of the memory set).” When results reached statistical significance for the illumination condition, we conducted subsequent analysis to reveal whether the effect was due to illuminance or color-temperature using a repeated measures ANOVA. We used the Greenhouse–Geisser correction where appropriate. The Bonferroni correction for multiple comparisons was applied in post hoc analyses.

RESULTS

We found significant differences in the accuracy of task performance ($F(2,38) = 15.835$, $p < 0.001$) and in reaction time ($F(2,38) = 22.137$, $p < 0.001$) across memory loads (i.e., the size of the memory set). This finding shows that higher memory loads resulted in lower accuracy and longer reaction times (cf. Fig. 2A, B). However, we detected no significant main effect of the illumination condition ($F(3,57) = 0.755$, n.s.), and found no interaction between the two factors ($F(6,114) = 1.299$, n.s.) in the accuracy of task performance. Similarly, there was no significant main effect of the illumination condition ($F(3,57) = 0.791$, n.s.) or significant interaction between the two factors ($F(6,114) = 1.906$, n.s.) with respect to reaction time.

With regard to the P1 amplitude, we observed no significant main effects of the illuminance ($F(3,57) = 1.789$, n.s.) and memory load factors

($F(2,38) = 1.426$, n.s.) with a marginally significant interaction effect ($F(6,114) = 2.045$, $p = 0.065$). Although there was no significant main effect of illuminance ($F(3,57) = 0.852$, n.s.) and an interaction effect ($F(6,114) = 0.544$, n.s.) in the P1 latency, we found that the memory load significantly influenced the P1 latency ($F(2,38) = 5.455$, $p < 0.01$; 3 set-size: 125.425 ms, 5 set-size: 130.925 ms, 7 set-size: 130.050 ms). Meanwhile, the illumination factor significantly modulated the N1 amplitude ($F(3,57) = 4.384$, $p < 0.01$; cool–dark: $-3.279 \mu\text{V}$, cool–bright: $-3.855 \mu\text{V}$, warm–dark: $-3.077 \mu\text{V}$, warm–bright: $-3.603 \mu\text{V}$). Subsequent tests indicated that this effect was due to the illuminance factor ($F(1,19) = 8.037$, $p < 0.05$; dark: $-3.178 \mu\text{V}$, bright: $-3.729 \mu\text{V}$), but not the color-temperature factor ($F(1,19) = 2.277$, n.s.). However, there was no significant main effect of the memory load ($F(2,38) = 0.679$, n.s.), and there was no significant interaction effect ($F(6,114) = 1.264$, n.s.) in the N1 amplitude. We found that the N1 latency was significantly altered by both illumination ($F(3,57) = 37.212$, $p < 0.001$; cool–dark: 176.467 ms, cool–bright: 187.433 ms, warm–dark: 176.767 ms, warm–bright: 188.367 ms) and memory load factors ($F(2,38) = 5.285$, $p < 0.01$; 3 set-size: 179.875 ms, 5 set-size: 184.225 ms, 7 set-size: 182.675 ms). Subsequent tests revealed that the bright condition produced a significantly delayed N1 latency ($F(1,19) = 50.186$, $p < 0.005$; dark: 176.617 ms, bright: 187.900 ms), but it was not affected by the color-temperature factor ($F(1,19) = 0.816$, n.s.). However, there was no significant interaction effect between these two factors with regard to the N1 latency ($F(6,114) = 0.583$, n.s.).

In addition, we found that the mean value of frontal EEG theta power was significantly modulated by both the illumination conditions ($F(3,57) = 2.896$, $p < 0.05$; Figs. 2 and 3; cool–dark: $10.309 \mu\text{V}^2$, cool–bright: $10.017 \mu\text{V}^2$, warm–dark: $12.205 \mu\text{V}^2$, warm–bright: $9.102 \mu\text{V}^2$) and the memory load ($F(2,38) = 3.834$, $p < 0.05$; 3 set-size: $9.123 \mu\text{V}^2$, 5 set-size: $10.646 \mu\text{V}^2$, 7 set-size: $11.455 \mu\text{V}^2$), indicating that higher memory loads resulted in a higher theta power. These results were attributable to illuminance ($F(1,19) = 4.585$, $p < 0.05$; dark: $11.257 \mu\text{V}^2$, bright: $9.560 \mu\text{V}^2$) and not to the color-temperature ($F(1,19) = 0.432$, n.s.). There was no interaction effect between the illumination and memory load factors in the frontal theta power ($F(6,114) = 1.917$, n.s.).

DISCUSSION

Consistent with previous studies (Sternberg, 1969; Jensen and Tesche, 2002), we observed significantly longer reaction times and elevated frontal theta power associated with increased memory load (i.e., set size). We also found that both ERP components and EEG theta activity were significantly modulated by the different illumination conditions without any significant concomitant changes in working memory task

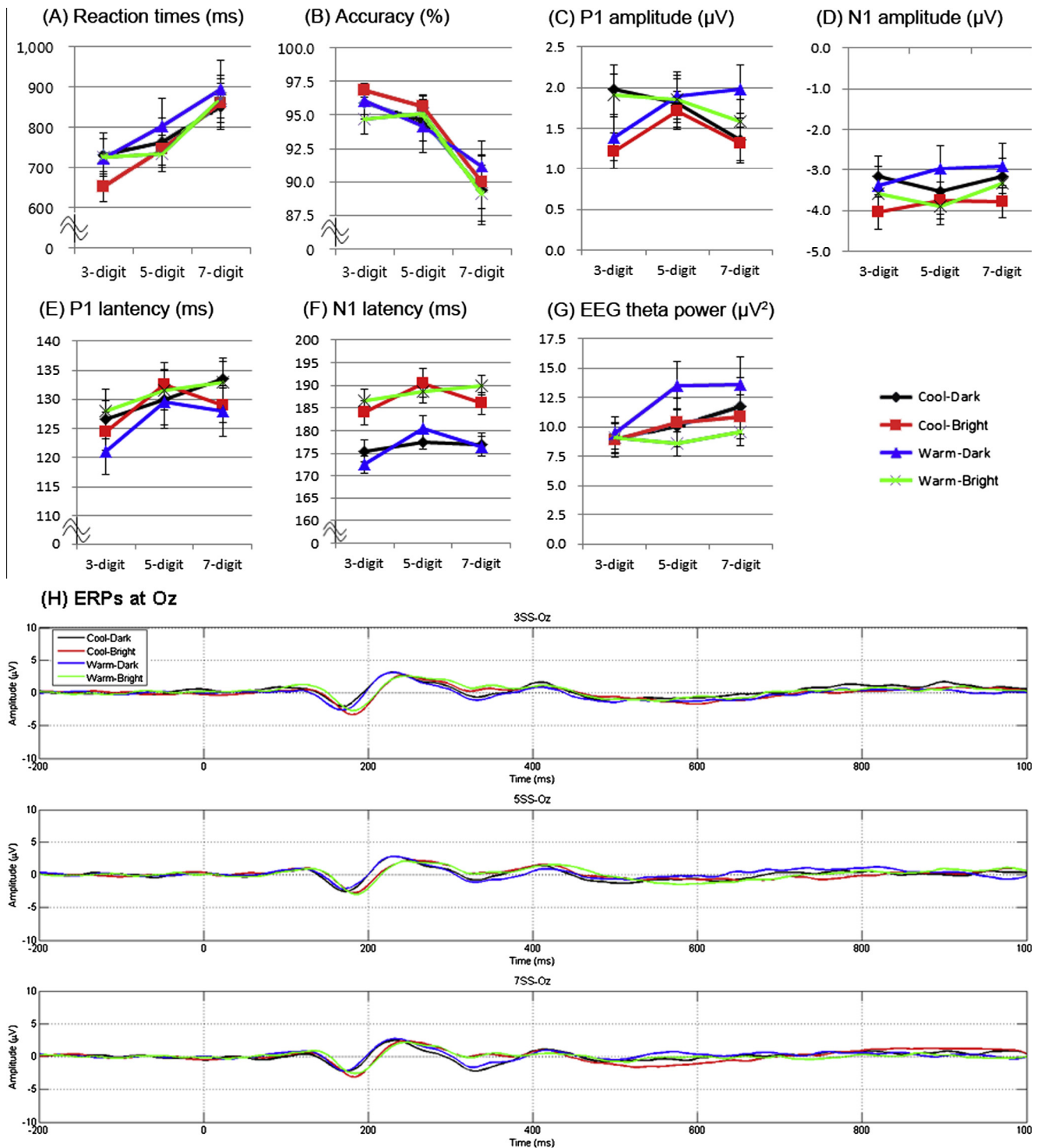


Fig. 2. Effects of illumination conditions (black: cool-dark, red: cool-bright, blue: warm-dark, green: warm-bright) and memory load (3, 5, 7-digit: 3SS, 5SS, 7SS, respectively) upon (A) reaction times, (B) accuracy of the task performance, (C) P1 amplitude, (D) N1 amplitude, (E) P1 latency, (F) N1 latency, and (G) power of EEG theta activity. Means and standard errors are shown. Grand-averaged ERPs at the electrode (H) Oz for the P1 and N1 components are shown (black line: cool-dark, red line: cool-bright, blue line: warm-dark, green line: warm-bright).

performance. Specifically, the brighter illumination condition was associated with longer occipital N1 latencies and lower frontal theta power in the retention period (cf. Fig. 2). The bright light-induced delay of the early ERP components did not significantly affect the participants' behavioral responses, such as accuracy

and reaction times. These results indicate that illumination conditions might not influence task performance, although they seem to interrupt early-evoked sensory processes, thus resulting in delayed latencies. Since the early ERP components behaved differently across experimental conditions, such

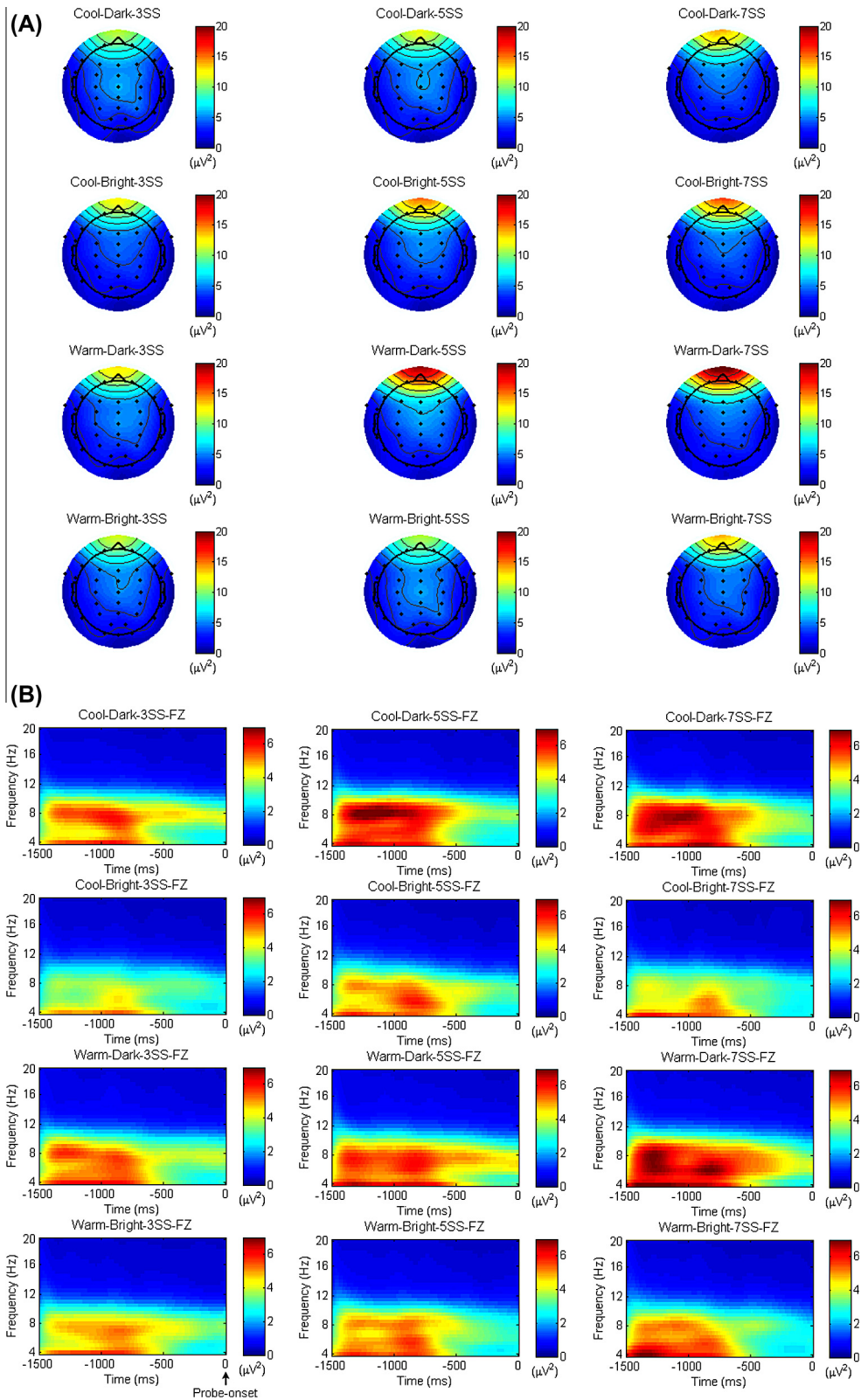


Fig. 3. (A) Grand-averaged scalp distributions (top-view) of theta activity (mean power from 800 to 200 ms prestimulus) and (B) their time–frequency representations of the electrode Fz with respect to the four illumination conditions and three memory set sizes during the Sternberg task. The rows of each table of the participants’ topographies and time–frequency plots indicate the illumination condition (from top to bottom: cool–dark, cool–bright, warm–dark, and warm–bright), while the columns represent the memory set size of 3 (far left: 3SS), 5 (middle: 5SS), and 7 (far right: 7SS). The time 0 in the time–frequency representation indicates the onset of probe-stimulus. The color-bar scale is μV^2 .

selective modulations of early ERP components may provide electrophysiological evidence of early dissociative mechanisms underlying the perception of brightness and the manipulation of working memory. Nevertheless, some responses reflected similar trends to the experimental conditions. For example, occipital N1 latencies were delayed in the bright lighting condition, and occipital P1/N1 latencies were delayed under a higher memory load. Although some ERPs were consistently modulated by illumination or memory load, future studies may better characterize each ERP component and their behavioral interactions.

Considering that illuminance significantly modulated both the amplitude and the latency of the occipital N1 component, the occipital area shows greater sensitivity to the external illumination condition than other cortical areas. This is expected because the occipital lobe processes most early visual information in the cortex, thus illumination may influence the occipital visual cortices more robustly than other brain regions. Since post hoc tests revealed that the illumination effect was due to the illuminance factor (and not the color-temperature factor), color-temperature exerted minimal influence on performance of the Sternberg working memory task. Given this finding, why did the brighter condition induce delayed early ERP latencies, as shown in higher working-memory loads? Although humans often experience bright illumination conditions that may increase the efficacy of work performance, the bright illumination condition used in the present study (700 lx) was presumably brighter than the illuminance of a comfortable office work (approximately 500 lx; Boyce, 2006). Therefore, the delayed N1 latencies observed in the present study might suggest that high illuminance influences normal attentional processing, since early ERP components may reflect sensory and attentional influences (Luck et al., 1990; Boop et al., 1994). The delayed N1 latencies were consistently observed during the target detection for stimuli presented against an isoluminant gray background as compared with a non-isoluminant dark background (Wijers et al., 1997). Their observations corroborate our findings that early selective processing relies upon bottom-up perceptual processing, and that brighter backgrounds delay N1 latencies.

The brighter illumination condition yielded significantly lower frontal EEG theta activity during the retention period, but was not associated with any significant alterations in the participants' performance. The lighting conditions used in the present study may not have been strong enough to influence the performance stage of behavioral processing. Frontal theta EEG activity is systematically associated with mental loads (Gevins et al., 1997; Jensen and Tesche, 2002; Onton et al., 2005). Therefore, our observation of reduced frontal theta power under the brighter illumination condition implies a reduction in the mental load required during the retention period of working memory, rather than the poststimulus processes indicated by the early ERP modulations. Nevertheless, the observed electrophysiological modulations following changes in

the illumination condition provides objective and substantial evidence that illumination conditions modulate our brain activity. As shown in Fig. 3, during the retention period, the early component of theta activity seems to be phasic (stimulus-locked) while the following sustained theta activity appears to be related to retention activity of the encoded information. However, since we compared the mean power of theta activity in the time window from 800 to 200 ms prior to the onset of probe stimulus, our observation might reflect sustained rather than phasic activity. Such sustained theta activity corresponds to information maintenance in working memory. Frontal theta activity has been reported to parametrically reflect working-memory load (Gevins et al., 1997; Jensen and Tesche, 2002). Frontal theta activity has often been reported to increase during difficult, attention-demanding tasks, and the ACC is its likely region of origin (Gevins et al., 1997; Ishii et al., 1999). The ACC is activated during the execution of working memory, and results in generating frontal midline theta activity (Onton et al., 2005). In order to efficiently perform the Sternberg working memory task, participants must pay attention to the information they might hold during the retention phase. Because attention plays a crucial role in controlling the activation, maintenance, and manipulation of mental representations in working memory (Kiyonaga and Egner, 2013) and the ACC is involved in the attentional network (Bryden et al., 2011; Totah et al., 2012), our observation of reduced frontal midline theta activity under the brighter illumination condition may indicate less efficient task performance. That is, the brighter illumination condition seems to interrupt task-induced attentional processing. In this respect, the observed delay of the N1 latencies with reduced theta activity may suggest possible disturbance of normal attentional processing by high illuminance.

Under the higher color-temperature condition in our study, the frontal theta activity during the bright illumination condition was only 74.6% compared to that observed during the dark condition. Under such bright illumination conditions, participants might require less mental loading (reflected in less power of frontal theta activity) to successfully perform the task. However, participants statistically attain the same level of task performance in both conditions, even though the dark condition may necessitate more frontal theta activity to accomplish the same task performance. Our results provide objective evidence that illumination conditions alter the working-memory load, which is reflected in EEG signals. Specifically, brighter illumination may reduce memory load. Nevertheless, the present study has some technical constraints that are worth mentioning. First, due to the technical limitations of the LED device, we were unable to investigate the full range of luminance values described by the Kruthof curve. Additional cognitive effects altered by illumination conditions may be discovered by future work that can systematically map as many illumination-parameter combinations as possible. Second, a limited number of illumination-parameter combinations were tested within

each participant because of the time limitations of an EEG experiment. Alternatively, a series of stepwise experiments could investigate the cognitive influence of each illumination-parameter combination. This study could be conducted in a line-by-line way. That is, the function of one-dimensional property of illumination could be examined when the other illumination parameters are held at a constant value. Lastly, several other possibilities may account for our observations of frontal theta modulation. For example, in the present study we simply manipulated the size of the memory set. However, there is a cognitive function related to processing of the presented items in working memory, and such cognitive function can be reflected in alternations of frontal midline theta activity. Furthermore, individual variances should be carefully examined to investigate their relevance in terms of cognitive processing. Therefore, we scrutinized all the participants' trends of frontal midline theta activity in relation to both illumination and memory-load conditions. Although there is a large variability over participants (Michels et al., 2008), we found the frontal theta activity was the dominant detectable spectral changes in relation to the Sternberg task in the present study.

CONCLUSIONS

Our observations provide substantial evidence that illumination conditions can significantly affect brain activity without significantly changing task performance. Presumably, the bright illumination condition influences poststimulus attentional processing (reflected in delayed N1 latencies), while simultaneously alleviating mental loads during the retention period (reflected in reduced frontal theta power). Future studies on how to improve the efficiency of cognitive performance by certain combinations of illumination parameters are required to facilitate appropriate applications to enhance work performance. For instance, our future work involves testing illumination-mediated applications to enhance work efficiency and treat stress within occupational and clinical environments.

CONFLICT OF INTEREST

All the authors declare that they have no competing interests.

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