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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 activity. Further studies are necessary to refine the optimal lighting parameters for facilitating working memory.

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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Abbreviations: ACC, anterior cingulate cortex; ANOVA, analysis of variance; EEG, electroencephalogram; ERP, event-related potential; LED, light-emitting diode.

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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 $60 \times 60\ cm^2$ 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