International Journal of Psychophysiology 104 (2016) 10–16

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Effects of light wavelength on MEG ERD/ERS during a working memory task

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ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form 29 March 2016
Accepted 29 March 2016
Available online 31 March 2016

Keywords:
Monochromatic light
Working memory
Event-related desynchronization/synchronization
Magnetoencephalography (MEG)

ABSTRACT

We investigated the effects of light wavelengths on cortical oscillatory activity associated with working memory processes. Cortical activity responses were measured using magnetoencephalography (MEG) while participants performed an auditory Sternberg memory task during exposure to light of different wavelength. Each trial of the memory task consisted of four words presented as a memory set and one word presented as a probe. All words were presented audibly. Participants were instructed to indicate whether the probe word was or was not presented within the memory set. A total of 90 trials were conducted under the light exposure. Event-related synchronization (ERS) and event-related desynchronization responses in the alpha frequency range during the task were analyzed. Results showed that, during memory encoding, ERS responses were significantly greater in the short-wavelength (blue) light condition than in the middle-wavelength (green) light condition, approximately 20–30 min after the onset of light exposure. Behavioral performance was very high throughout the experiment and there was no difference between the light conditions. Although the light effects were not observed in behavior, the result of ERS suggests that 20–30 min of exposure to blue light enhances cortical activity related to active memory maintenance and/or attention to auditory stimuli.

1. Introduction

Ocular exposure to bright white light during the night increases human alertness more than exposure to dim light does, as shown by a greater reduction of subjective sleepiness, increase in task performance, increase in body temperature and heart rate, reduction of low-frequency (theta and alpha range) electroencephalography (EEG) activity, reduction of the incidence of slow-eye movements, and suppression of melatonin level (Campbell and Dawson, 1990; Badia et al., 1991; Thessing et al., 1994; Cajochen et al., 1998, 2000; Daurat et al., 2000; Lowden et al., 2004). The alerting effects of light are dependent of the wavelength of the light. Nighttime melatonin secretion in humans is most effectively suppressed by exposure to short-wavelength (blue monochromatic) light (Brainard et al., 2001; Thapan et al., 2001). Studies comparing the effect of light of different wavelengths have also shown that short-wavelength light has a greater nighttime alerting effect than middle-wavelength (green monochromatic) light or darkness (Cajochen et al., 2005; Lockley et al., 2006; Figueiro et al., 2009). Mammalian intrinsically photosensitive retinal ganglion cells (ipRGCs), which innervate the suprachiasmatic nucleus, exhibit a peak in spectral sensitivity for short-wavelength light (Berson et al., 2002). Because the suprachiasmatic nucleus is a principal circadian pacemaker, it is assumed that the system involving ipRGCs possibly mediates the alerting effects of light (Cajochen, 2007).

Most studies of the effects of light exposure on alertness have been performed during the nighttime, because the effects of light can be more easily observed at this time, when human alertness levels are low. However, studies that compared the effects of light exposure during daytime and nighttime showed that exposure to bright white light or blue monochromatic light during the daytime also improved alertness, although there were no differences in some psychological and physiological responses (Ruger et al., 2006, Rahman et al., 2014). Moreover, a study using functional magnetic resonance imaging (fMRI) indicated that daytime exposure to a bright white light enhanced activity of brain areas engaged by an oddball task (Vandewalle et al., 2006). In addition, fMRI studies of monochromatic lights exposure in the daytime showed that activity of brain areas implicated in a working memory task was greater during exposure to 470-nm blue light than during exposure to 550-nm green light (Vandewalle et al., 2007a), 520-nm green light (the peak sensitivity of M-cones), or 430-nm violet light (the peak sensitivity of S-cones) (Vandewalle et al., 2007b). These fMRI findings suggest that, even in the daytime when melatonin levels are low, exposure to light enhances activity of brain areas involved in cognitive processes, and that blue light has the largest moderating effect. They also suggest that the effects of light exposure on cognitive

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http://dx.doi.org/10.1016/j.ijpsycho.2016.03.008
0167-8760/

brain activity likely rely on neural pathways from ipRGCs that project broadly throughout the brain (Vandewalle et al., 2007a, 2007b). Studies using event-related potential (ERP) have suggested that exposure to blue light elicits larger P300 amplitude during an oddball task than exposure to lights with other wavelengths (An et al., 2009, Okamoto and Nakagawa, 2015). More information about how light modulates brain activity during cognitive processing is needed to elucidate the effects of light on cognition.

The functioning of the dynamic and distributed neural processes in the brain that underlie mental processes can be assessed by studying ongoing electrical brain oscillations at different frequencies while participants are engaged in cognitive processing (Krause, 2006). One way to assess changes in electrical brain oscillations in response to a particular event is to investigate a decrease or increase of the oscillatory responses in different frequency bands, and this can be measured by EEG or magnetoencephalography (MEG). A relative decrease in the power in a certain frequency band is called event-related desynchronization (ERD), whereas a relative increase in the power is called event-related synchronization (ERS) (Pfurtscheller, 1977; Pfurtscheller and Aranibar, 1977; Pfurtscheller and Lopes da Silva, 1999). Krause and co-workers used the ERD/ERS technique to investigate changes in brain oscillatory activity during auditory working memory processing (Krause et al., 1995, 1996, 1999, 2001, 2002; Karrasch et al., 1998, 2004, 2006). They have frequently use a Sternberg memory search paradigm (Sternberg, 1966), in which auditory memory set items were presented (encording) and then the participant decided whether a following probe item was or was not presented within the memory set (retrieval). Their results showed that auditory memory encoding typically elicited ERS in the alpha frequency range (8–12 Hz), whereas memory retrieval and comparative mental process elicited ERD in the alpha frequency range (Krause et al., 1995, 1996). Moreover, it has been reported that alcohol, age and cognitive disease modulate ERD/ERS during an auditory Sternberg task (Krause et al., 2002; Karrasch et al., 2004; Krause et al., 2001; Karrasch et al., 2006).

The present study aimed to examine how monochromatic light exposure affects dynamic and distributed brain oscillatory activity during a sequential memory process such as memory encoding and retrieval, using the ERD/ERS technique. We used blue monochromatic light because it has been shown to enhance activity of brain areas implicated in a cognitive task (Vandewalle et al., 2007a, 2007b). Green monochromatic light, which the photopic system is most sensitive to, was used for comparison. We measured MEG responses while participants performed an auditory Sternberg memory task while exposed to light with these two different wavelengths. ERD/ERS of MEG during the task was compared across the light conditions.

2. Materials and methods

2.1. Participants

Twelve male adults ranging in age from 20 to 31 years (mean age 22.4 years) participated in this study. All participants were nonsmokers, and were instructed to refrain from consuming caffeine or alcohol during the 12-h period preceding the experiments. Participants were asked about their usual wake-up time and the time at which they awoke on the days of the experiments. Mean and standard error of the mean (SEM) wake-up time on the days of the experiments was 08:25 (22 min) and the deviance of wake-up time from the usual wake-up time was 8 min (17 min).

This study had prior approval from the Ethical Committee of the Kansai Research Center, National Institute of Advanced Industrial Science and Technology, Japan. Written informed consent was obtained from each participant after an explanation of the nature and purpose of the investigation.

2.2. Procedures

The experiment was conducted on two different days for each participant. The experimental paradigm was identical on both days except for the wavelength of light to which the participant was exposed: short or middle wavelength (i.e., blue or green). In a magnetically shielded room, participants were asked to sit in front of a light diffusion panel and then sat in darkness for approximately 10 min. Then, a monochromatic light with one of two wavelengths was presented for approximately 30 min, as shown in Fig. 1. The order of the light conditions was counterbalanced across participants. On each day, the experiment was conducted for approximately 40 min between 14:00 and 16:00.

A blue or green monochromatic light emitted by LEDs was projected on the diffusion panel from the back of the panel. The panel was placed 70 cm from the participant's eyes. The visual angle of the light stimuli was 75 deg vertically and horizontally. Because the intensity and spectral property of the lights could not be measured in the magnetically shielded room, they were estimated in another room with a similar environment to the magnetically shielded room, using an illuminance spectrophotometer (CL-500A, Konica Minolta, Japan). The estimated irradiance of both lights was 3.6 $\mu W/cm^2$. The peak wavelength for the blue and green lights was 470 and 520 nm, respectively, with a full width half maximum of 22 and 35 nm, respectively.

Participants performed a modified version of Sternberg memory search paradigm (Karrasch et al., 2004, Sternberg, 1966). In each trial of the task, four auditory stimuli were presented as memory set items and then an auditory stimulus was presented as a probe item. Participants were instructed to indicate whether the probe item from the memory set or not by pressing one of two buttons. The auditory stimuli were Japanese four-mora words recorded in a female voice. The words were chosen from a commercially available database (FW03, NTT Advanced Technology Corporation, Japan), in which words are categorized in four word-familiarity ranks. Familiarity is a subjective rating of how often people encounter a word in everyday life. To control the task difficulty, we selected 50 words categorized in the same familiarity rank, which is the highest rank. In each trial, the four words in the memory set were chosen randomly from the 50 words so that the same word did not appear more than twice. In 50% of trials, the probe word was from the four-word memory. The auditory stimuli were delivered binaurally through insert earphones (E-A-RTONE 3A, Etymotic Research, IL, USA). The intensity of the stimuli was assessed by an ear simulator (type 4159, Brüel & Kjær, Denmark) and a conditioning amplifier (NEXUS type 2690, Brüel & Kjær, Denmark) and set to 73 dB SPL.

During the task, participants were asked to fixate on a small white mark with a visual angle of 0.7 deg vertically and horizontally that appeared at the center of the diffusion panel. Participants were advised to refrain from head and body movements as much as possible to prevent motion-related interference with the MEG signal. Each trial began with an inter-trial interval of 3000 ms. Then, the fixation mark expanded to a visual angle of 2 deg vertically and horizontally over 200 ms to indicate that the memory set was about to be presented. After 2000 ms, the four-word memory set was presented. The mean

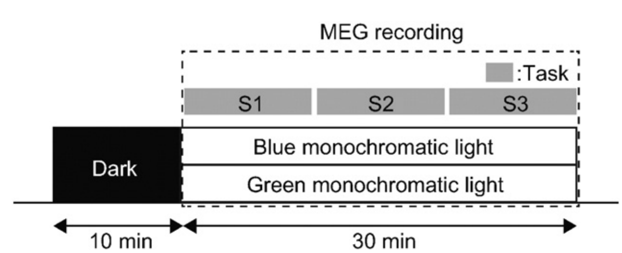

Fig. 1. Experimental design. Gray rectangles indicate the task periods. MEG was recorded during three task periods (three sessions) while the participant exposed to blue monochromatic (short-wavelength) or green monochromatic (middle-wavelength) light. S1–S3: sessions 1–3.