

Effects of Daytime Exposures to Short- and Middle-wavelength Lights on Cortical Activity during a Cognitive Task*

Yosuke Okamoto, Seiji Nakagawa

Abstract— This study aimed to assess the effects of light wavelength on human cortical activity during a cognitive task, by observing event-related potentials (ERPs). We measured ERPs when subjects perform an auditory oddball task under daytime exposures to short- and middle-wavelength lights. In the oddball task, a standard tone of 1 kHz and a target tone of 2 kHz were used. Subjects were instructed to press a button as soon as they heard the target tone. The ERP component that occurs approximately 300 ms after a stimulus onset (P300) was analyzed. The results showed that amplitude of P300 in the short-wavelength light condition was significantly larger than that in the middle-wavelength light condition approximately 10–20 min after the start of light exposure. It has been suggested that the amplitude of P300 reflects the amount of attentional resources for a given task. Therefore, the results obtained suggest that amount of attentional resource allocated to the oddball task is increased during exposure to the short-wavelength light in the daytime.

I. INTRODUCTION

It is known that ocular exposure to light affects human behavioral and physiological function. For example, previous studies have found that exposure to bright white light during nighttime reduce subjective sleepiness, increase core body temperature, suppress melatonin level, reduce low frequency activity of electroencephalograph (EEG) [e.g. 1, 2]. Recently, it has been shown that such alerting effects of light are dependent on wavelength of light. Nighttime melatonin secretion in humans is suppressed most effectively by short-wavelength (blue) light [3, 4]. Melatonin suppression is assumed to contribute strongly to the alerting effects at night. Actually, it has been shown that the light with short wavelength elicits stronger nighttime effects on alertness than the middle-wavelength (green) light or darkness [5-7]. Mechanisms underlying alerting effect of light at nighttime are becoming clear. Mammalian intrinsically photosensitive retinal ganglion cells (ipRGCs) innervating the suprachiasmatic nucleus (SCN) exhibit a peak in spectral sensitivity for short-wavelength (blue) light [8]. This finding suggest that signal inputs from ipRGCs play an important role in modulating alertness, because the SCN is a circadian pacemaker and indirectly drives melatonin secretion from the pineal gland.

*Resrach supported by JSPS KAKENHI.

Y. Okamoto is with National Institute of Advanced Industrial Science and Technology (AIST), Ikeda, Osaka 5638577 Japan (corresponding author to provide phone: 072-751-9527; fax: 072-751-9517; e-mail: yos-okamoto@aist.go.jp).

S. Nakagawa is with National Institute of Advanced Industrial Science and Technology (AIST), Ikeda, Osaka 5638577 Japan (e-mail: s-nakagawa@aist.go.jp).

Compared to the light effects on alertness at night, not much is known about the alerting effects of light in the daytime, when melatonin secretion is low. Studies of subjects in the daytime have reported no difference in the effects of bright white light and dim light on alertness [9, 10]. However, one study on the impact of daytime exposure to bright white light compared to a low intensity control condition has reported that subjective sleepiness, the incidence of slow-eye movements (SEMs) and reaction time measured in sleep restricted subjects were reduced by bright light exposure, although melatonin levels did not change between the two light conditions [11]. It may be more difficult to observe the alerting effects of light during the daytime, when alertness levels are naturally increased. However, light exposure seems to modulate not only alertness but also cognitive processes. A study using functional magnetic resonance imaging (fMRI) has indicated that daytime exposure to bright white light enhances brain activity during a cognitive task [12]. Moreover, during the daytime, fMRI studies have shown that brain activity in areas implicated in cognitive tasks is modulated effectively by exposure to the short-wavelength light [13, 14]. These findings imply that the light, especially with short wavelength, can affect human cognitive function even when melatonin secretion is low. However, the behavioral and physiological changes related to cognitive processes that are affected by daytime light exposure remain unclear, compared to those on alertness at night. In addition, few attempts have been made to elucidate the temporal dynamics of the effects of light wavelength on cognition, whereas the temporal dynamics of alertness under exposure to different-wavelength lights have been investigated.

This study aimed to examine the temporal dynamics of cortical activity related to the effects of light wavelengths on cognitive function in the daytime, by observing event-related potentials (ERPs). The ERP component of EEG that occurs approximately 300 ms after a stimulus onset (P300) has been employed as a neurophysiological measure of cognitive processing. It has been proposed that the amplitude of the P300 elicited by an oddball task reflects the amount of attentional allocation resources. When ERPs elicited by an oddball task are measured while a subjects performs a primary task, the P300 amplitude decreases as the difficulty of the primary task increases [15-18].

We used two monochromatic lights; one has a short wavelength, to which ipRGCs are most sensitive, and another has a middle wavelength, to which ipRGCs are less sensitive. Under these light conditions, ERPs were recorded while subjects performed an auditory oddball task. ERP measurements were conducted in separated periods during a session, and time course of an ERP component was investigated.

II. METHODS

A. Subjects

Eight male adults participated in the study. Age ranged from 19 to 37 years. All participants were nonsmokers, and were instructed to refrain from consuming caffeine or alcohol during the 12 h period preceding the experiments.

B. Protocol

This study consisted of two different sessions, and all sessions were conducted between 12:00 and 16:00. In each session, subjects sat in front of the light source. Darkness was maintained for the first 10 min. Then, monochromatic light with one of two wavelengths (short or middle) was presented for 28 minutes. During each session, ERP measurements were conducted in the last part of the dark period, repeated four times, as shown in Figure 1. The duration and interval of ERP measurements were set at approximately 4 min and 3 min, respectively.

C. Auditory stimuli

During the ERP interval, subjects performed an auditory oddball task. In this task, we used a standard tone of 1 kHz and a target tone of 2 kHz. The interstimulus interval was 1 s. The probability of a standard tone was 0.8 and that of a target tone was 0.2. Intensities of the stimuli were set to 80 dB SPL. Standard and target tones were presented in random order more than 160 and 40 times in each ERP interval, respectively. Subjects were instructed to press a button as soon as they heard the target tone.

D. Light sources

Two light sources with short and middle wavelengths were presented to subjects via a light guide panel. The light emitted from LEDs placed at the side of the panel radiated through the diffusion sheet in the panel, and then a uniform and non-glaring distribution of light was created on the surface of the panel. As shown in Figure 2, the peak intensity for the short and medium wavelength lights was 470 and 530 nm, respectively. The illuminance levels of the lights were set at 10 lux at the cornea.

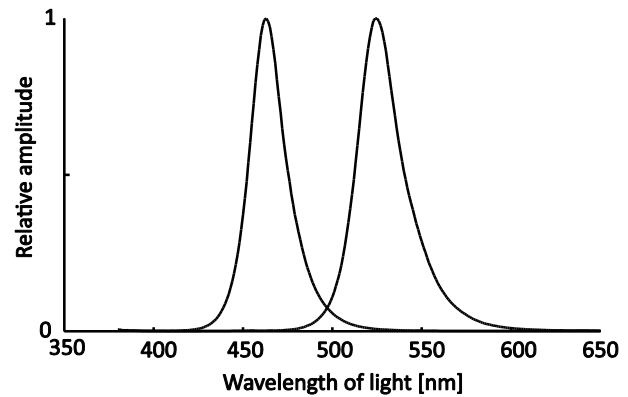


Figure 2. Spectral distribution of light sources.

E. EEG recording

EEG activity was recorded from an electrode placed at Fz, Cz and Pz, according to the International 10-20 system. Reference electrodes were placed on the left and right ear lobes, and a ground electrode was placed on the forehead. Impedances were kept below 5 k Ω . EEG data were digitized with a sampling rate of 1 kHz. The EEG data were band-pass filtered between 0.3 and 30 Hz.

F. ERP analysis

ERPs to the target stimulus were obtained by extracting the EEG epoch of 200 ms prior to stimulus onset through 800 ms post-stimulus, relative to a 200 ms prestimulus baseline. In order to avoid artifacts, EEG epochs with amplitudes exceeded $\pm 150 \mu\text{V}$ were excluded from the average. Each ERP consists of at least 40 epochs. P300 was identified as the most positive-going peak in the ERP waveforms between 250 and 450 ms post stimulus onset, as shown in Figure 3.

III. RESULTS

To compare time courses of amplitudes of P300 across light conditions, the P300 amplitude for each time interval was normalized using the amplitude during the first dark interval. The normalized amplitudes of P300 were modulated by the short-wavelength light in all EEG electrodes. Therefore, the normalized P300 amplitudes were averaged over all EEG electrodes for each light condition. Time courses of the normalized P300 amplitudes were shown in Figure 4.

The effects of light condition and time interval on P300 amplitude were assessed using a repeated-measures analysis of variance (ANOVA) with light condition (short- and middle-wavelengths) and time interval (5 ERP intervals) as factors. The ANOVA showed a significant main effect of time interval ($p < 0.01$). However, a main effect of light condition was not significant. There was also a significant interaction between light condition and time interval ($p < 0.05$). Therefore, we conducted tests of simple main effects. The results showed that the P300 amplitude during the short-wavelength light condition was significantly larger than that for the middle-wavelength light condition in the 3rd and 4th ERP intervals (i.e. approximately 10–20 min after exposure) ($p < 0.05$).

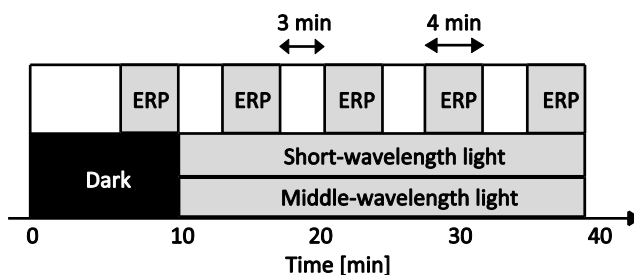


Figure 1. Experimental protocol. Gray rectangles indicate ERP measurement periods.

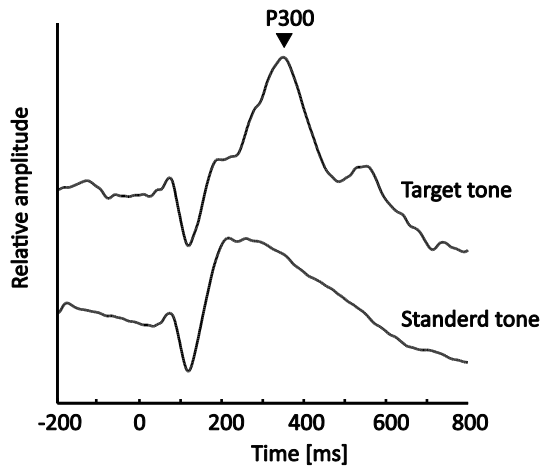


Figure 3. The averaged ERP waveforms from all electrodes during middle-wavelength light condition. The upper and lower lines illustrate ERPs to the target and standard tones, respectively.

IV. DISCUSSIONS

The present results showed that P300 amplitude for the short-wavelength light was significantly larger compared to the middle-wavelength light condition approximately after 10–20 min of light exposure. It has been suggested that the amplitude of the P300 reflects the amount of attentional resources required to attend to the probe stimuli [19, 18]. Therefore, the present findings suggest that amount of attentional resource allocated to the oddball task is increased during exposure to the short-wavelength light in the daytime. It has been supposed that overall arousal level determines the amount of processing capacity available for attention allocation to on-going task and attentional resources are allocated depending on the amounts of these that tasks required [20]. It is difficult to determine based on the present results that the increase of the attentional resources to the oddball task is caused by the decrease of the demand of attentional resources that required by viewing the short-wavelength light source or by the increase of arousal level that governs the processing capacity by exposure to the short-wavelength light. Previous fMRI studies have shown that cortical activity in areas implicated in the cognitive task was enhanced more by the short-wavelength light than by the middle-wavelength light [13, 14]. Therefore, the present results can be interpreted that exposure to the short-wavelength light enhances arousal level, and as a result of that, the cortical activities involved in processing of a cognitive task are increased.

Previous fMRI studies have shown that cortical activity in areas implicated in cognitive tasks is modulated effectively by exposure to the short-wavelength light [13, 14]. Therefore, it has been suggested that signal inputs from ipRGCs strongly contribute to the effects of light on cognitive processing during the daytime, as proposed in the effects of light on alertness during nighttime. The present results showed that the P300 amplitude, which is thought to reflect cognitive processing, was modulated when subjects were exposed to short-wavelength light. This supports the suggestion that

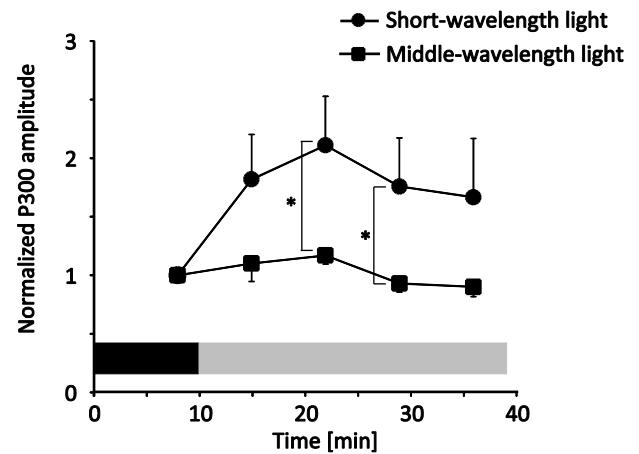


Figure 4. Normalized P300 amplitudes during exposure to light with a short- (circles) and a middle- (squares) wavelength. Black and gray bars indicate the dark adaptation period and the light exposure period, respectively. Error bars indicate 1 SEM (* $p < 0.05$).

ipRGCs play an important role in the effects of light on cognitive processes during the day.

Previous studies showing the time course on the nighttime alerting effects of the short-wavelength light have reported that the significant effect appeared in a melatonin suppression and subjective sleepiness rating 30 min after the start of light exposure and in the core body temperature and heart rate 1 h and 1.5 h after lights on, respectively [4]. On the other hand, the time course of ERP component P300 in the present study indicated that the effect of short-wavelength light on cognition became apparent almost right after the start of light exposure and significant approximately 10–20 minutes after the start of exposure. Moreover, it has been reported that 18 min exposure and recurring 50 s exposure to the short-wavelength light in the day enhance cortical activities related to cognitive processes [13, 14]. Although the duration in which the light effect need to be reflected might vary according to these psychological and physiological responses, there is a possibility that daytime effect of light on cognitive process become apparent in shorter time, compared to the nighttime effect of light on alertness.

V. CONCLUSION

We investigate the effects of light wavelengths on cognitive processes during the daytime, using short- and middle-wavelength lights. ERPs were obtained while participants performed an auditory oddball task during exposure to these lights. The P300 amplitude during exposure to short-wavelength light was larger than that during exposure to middle-wavelength light approximately 10–20 min after the start of light exposure. These results suggest that amount of attentional resource allocated to the cognitive task is increased by daytime exposure of 10–20 min to the short-wavelength light. This finding supports the suggestion that ipRGCs play an important role in the light effects on cognitive processes during the day.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number 23860073.

autonomic nervous system approaches, J. R. Jennings, M. G. H. Coles, Eds. New York: Wiley, 1991, pp. 179–241.

[20] D. Kahneman, *Attention and effort*. Englewood-Cliffs: Prentice Hall, 1973.

REFERENCES

- [1] C. Cajochen, J. M. Zeitzer, C. A. Czeisler, D. J. Dijk, “Dose–response relationship for light intensity and ocular and electroencephalographic correlates of human-alertness”, *Behav. Brain Res.*, vol. 115, pp. 75–83, Oct. 2000.
- [2] C. Cajochen, K. Kräuchi, K. V. Danilenko, A. Wirz-Justice, “Evening administration of melatonin and bright light: interactions on the EEG during sleep and wakefulness”, *J. Sleep Res.*, vol. 7, pp. 145–157, Sep. 1998.
- [3] G. C. Brainard, J. P. Hanifin, J. M. Greeson, B. Byrne, G. Glickman, E. Gerner, M. D. Rollag, “Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor”, *J. Neurosci.*, vol. 21, pp. 6405–6412, Aug. 2001.
- [4] K. Thapan, J. Arendt, D. J. Skene, “An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans”, *J. Physiol.*, vol. 535, pp. 261–267, Aug. 2001.
- [5] C. Cajochen, M. Munch, S. Kobińska, K. Krauchi, R. Steiner, P. Oelhafen, S. Orgul, A. Wirz-Justice, “High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light”, *J. Clin. Endocrinol. Metab.*, vol. 90, pp. 1311–1316, Mar. 2005.
- [6] S. W. Lockley, E. E. Evans, F. A. Scheer, G. C. Brainard, C. A. Czeisler, D. Aeschbach, “Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans”, *SLEEP*, vol. 29, pp. 161–168, Feb. 2006.
- [7] M. G. Figueiro, A. Bierman, B. Plitnick, M.S. Rea, “Preliminary evidence that both blue and red light can induce alertness at night”, *BMC Neurosci.*, vol. 10:105, Aug. 2009.
- [8] D. M. Berson, F. A. Dunn, M. Takao, “Phototransduction by retinal ganglion cells that set the circadian clock”, *Science*, vol. 295, pp. 1070–1073, Feb. 2002.
- [9] P. Badia, B. Myers, M. Boecker, J. Culpepper, “Bright Light Effects on Body Temperature, Alertness, EEG and Behavior”, *Physiol. Behav.*, vol. 50, pp. 583–588, Sep. 1991.
- [10] A. Daurat, A. Aguirre, J. Foret, P. Gonnet, A. Keromes, O. Benoit, “Bright light affects alertness and performance rhythms during a 24-h constant routine”, *Physiol. Behav.*, vol. 53, pp. 929–936, May 1993.
- [11] J. Phipps-Nelson, J. R. Redman, D. J. Dijk, S. M. W. Rajaratnam, “Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance”, *SLEEP*, vol. 26, pp. 695–700, Jun. 2003.
- [12] G. Vandewalle, E. Baeteau, C. Phillips, et al., “Daytime light exposure dynamically enhances brain responses”, *Curr. Biol.*, vol. 16, pp. 1616–1621, Aug. 2006.
- [13] G. Vandewalle, S. Gais, M. Schabus, et al., “Wavelength-dependent modulation of brain responses to a working memory task by daytime light exposure”, *Cereb. Cortex*, vol. 17, pp. 2788–2795, Dec. 2007.
- [14] G. Vandewalle, C. Schmidt, G. Albouy, et al., “Brain responses to violet, blue and green monochromatic light exposures in humans: Prominent role of blue light and the brainstem”, *PLoS One*, vol. 11, pp. 1–10, Nov. 2007.
- [15] J. B. Isreal, G. L. Chesney, C. D. Wickens, E. Donchin, “P300 and tracking difficulty: evidence for multiple resources in dual-task performance”, *Psychophysiology*, vol. 17, pp. 259–273, May 1980.
- [16] A. F. Kramer, C. D. Wickens, E. Donchin, “An analysis of the processing requirements of a complex perceptual-motor task”, *Hum. Factors*, vol. 25, pp. 597–621, Dec. 1983.
- [17] A. F. Kramer, E. J. Sirevaag, R. Braune, “A psychophysiological assessment of operator workload during flight missions”, *Hum. Factors*, vol. 29, pp. 145–160, Apr. 1987.
- [18] C. D. Wickens, A. F. Kramer, L. Vanasse, E. Donchin, “Performance of concurrent tasks: a psychophysiological analysis of reciprocity of information processing resources”, *Science*, vol. 221, pp. 1080–1082, Jul. 1983.
- [19] A. F. Kramer, J. Spinks, “Capacity views of human information processing”, in *Handbook of cognitive psychophysiology: central and*