Effects of Monochromatic Light on Different Time Perception

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Abstract

Time is a fundamental dimension of life. Previous studies reported that time perception is affected by several physiological and psychological factors (age, gender, time of day, flickering stimulus, etc). Light exerts visual and non-visual effects with respect to biological rhythms. However, it has not been confirmed that perception of the passage of time could be affected by the light environment. In this study, we investigated the physiological and psychological responses when subjects were exposed to different monochromatic light environments (there were four conditions of light intensity that varied by illuminance and irradiance). We evaluated the time sense by time tests of 180 s and 600 s. The results showed that the time sense runs significantly faster in a red light condition than in any other monochromatic light condition (green, blue I and blue II which is approximate half irradiance compared with blue I) in a 180-s time production task. However, in the 600-s estimation time task, the time sense tended to be significantly faster in the red light condition than in the blue I or blue II light conditions, and in the green light condition the time sense ran significantly faster than in the blue I light condition. There was no significant difference in color factor in P300 which is one of evoked potential components measured with electroencephalography (EEG), however, a significant trend was found in amplitudes of P300, which showed that the cognitive level tended to be high in the blue II light condition. The EEG alpha wave amplitude significantly increased in the green light condition compared to the amplitude in the blue I light condition. The results of SDPTG which is an index of autonomic nervous system measured with photoplethysmography (PPG), in which there was a significant trend to be faster in the blue I light condition than in the green or blue II light conditions, showed that blue light might have a sympathomimetic effect. There was no significant difference in color factor in the subjective assessments, except the subjects felt more eyestrain in the blue II than in the red light condition. These results indicate that the perception of the passage of time ran faster in the red-light than in the other light conditions. We suggest that red light has an active effect in a short time interval through the visual processing pathway and decays with time. The blue light seems to have a sustained effect on the central nervous system, but people may not be responsive to a short time interval exposure to blue light.

Keywords: monochromatic light, time intervals, color effect, time production task, time estimation task, P300, EEG, PPG

1. Introduction

Light can elicit acute physiological and psychological responses in human beings. The magnitude of responses depends on the color temperatures, intensity, wavelength components and duration of light exposure (Noguchi and Sakaguchi, 1999; Katsuura et al., 2005). Recent studies have found an effect of the light wavelength on suppression and phase delay of the melatonin rhythm (Morita and Tokura, 1998; Brainard et al., 2001; Lockley et al., 2003, 2006; Hamifin et al., 2006). Likewise, some studies have found effects of monochromatic light on the central nervous system. However, the results are not all in agreement with each other. For example, there was a greater recovery in the alpha wave under red light than under blue light presentation (Ali, 1972). In contrast, one study showed that the alpha band power density was higher in blue light than in green light (Lockley et al., 2006).

Timing and time perception are fundamental to survival and goal reaching in humans and other animals
and are affected by age and sex (Espinosa-Fernandez et al., 2003; Hancock and Rausch, 2010). They are possible over multiple timescales, owing to the number of biological mechanisms that have evolved to deal with time (Catalin et al., 2005). Circadian, interval and millisecond timing involve different neural mechanisms (Hinton and Meck, 1997). In mammals, the circadian clock, which drives metabolic and behavioral rhythms, is located in the suprachiasmatic nucleus (SCN) of the hypothalamus. This master clock coordinates tissue-specific rhythms according to light input (Reppert and Weaver, 2002) and other cues — such as social information — that it receives from the outside world (Levine et al., 2002). Interval timing depends on an intact striatum but not on an intact SCN or cerebellum (Lewis et al., 2003; Malapani et al., 1998; Harrington et al., 2004). In the interval-timing range, the striatum and the cerebellum might both be activated, possibly contributing to different aspects of performance (Spencer et al., 2003; Jueptner and Weiller, 1998). In recent studies, the judgment of short interval times has shown a substantial connection with neurons in a distributed network.

It has been verified that different light conditions could affect cortical activity. Therefore, the time sense might be affected by lighting conditions. A previous study (Katsuura et al., 2007) described activation in the central nervous system based on the evidence of P300 event-related potential. The latency of P300 under red light exposure was shorter than that under blue light exposure, according to the results of time-production tests lasting 180 s. The powers of the red light and blue light exposure were unified by the illuminance. In this study, we aligned the measurement unit of monochromatic light exposure with illuminance (red, green and blue I conditions) and irradiance (red and blue II conditions) to verify the differences between the two types of unit. We examined the time sense using a 180-s time task and a 600-s time task. We recorded the physiological indices of the activities of the central nervous system by EEG, P300 and the activities of the autonomic nervous system by finger PPG.

2. Methods

2.1. Subjects

Six healthy young adult volunteers (all males), age 25-27 years, participated in the present study. They were sufficiently informed of the experimental procedure and gave informed consent for study participation. They were not allowed to perform physical exercise or to consume alcoholic drinks or caffeine-containing food the previous experiment day.

2.2. Measurements

Twenty-five monochromatic LED lights were set in front of subjects. To ensure even illumination, we put a filter between the light source and the subjects. To verify the different unit effects, we composed measurement units of the LED light power as illuminance (red, green and blue I) and irradiance (red and blue II). The spectral distribution curves are shown in Figure 1 (peak wavelength: red 636 nm, green 527 nm, blue I-II 463 nm). The irradiance and the illuminance of the four light conditions which was measured with a spectroradiometer (HSR-8100, Opto Research Co.,) are shown in Table 1. Before the experiment, fluorescent lamps (5700 K) in a climatic chamber (25 °C, 50 % relative humidity) were turned on to stabilize the illuminance (312 lx). Each subject entered and sat on a comfortable chair 30 min before the experiment. During the 30 min we attached EEG electrodes on Fz, C3, Cz and C4 recording sites based on the International 10/20 system and the PPG sensor.

During the experiment, the subject sat quietly on a chair for 30 min under baseline conditions. Thirty minutes later, the fluorescent lamps were turned off, and then the monochromatic lights were turned on and stayed on until the experiment ended. During the experiment, we examined the EEG (alpha wave band power ratio, 8–13Hz), P300 event-related potentials (1000Hz and 2000Hz target sound, 65dB SPL auditory stimuli by an earphone), and SDPTG (Second Derivative of the finger Plethysmogram taken from the cuticle of the left forefinger: the index ($-b/a$) was calculated based on the wave height from the PPG). The experimental protocol is shown in Figure 2. There were four conditions (Red, Green, Blue I and Blue II). All the experiments were conducted during the same

![Fig. 1 Spectral distribution curves of the red ( ), green ( ), blue I ( ) and blue II ( ) light conditions.](image)

| Table 1 | Illuminance and irradiance of red light, green light, blue I light and blue II light conditions. |
|---------|--------------------------------------------------|
| Illuminance (photopic-lx) | Irradiance (μWcm²) |
| red light | 37 | 22 |
| green light | 36 | 6 |
| blue I light | 38 | 52 |
| blue II light | 7 | 24 |
hours (13:00-15:00) but on separate days. To consider the influence of the experiment day compared to the next day, the interval experimental date was above 3 days between each two sets of conditions. The order of color conditions was counterbalanced among the subjects.

In the psychological estimation, we used visual analogue scales (VAS) to assess feelings of arousal level, fatigue, stress, eyestrain and concentration in the baseline condition and at the end of the experiment. Feelings of favorite light condition, brightness of light condition, the longest and shortest length of time-past for each condition were asked only at the end of the experiment.

**Time tasks:** As shown in Figure 2, time tasks were begun 32 min after the experiment started. The subjects were asked to produce two 180-s time intervals and one 600-s time interval by a stopwatch. The display of the stopwatch was covered by a seal to mask the digits of time. In the 180-s time production task (Tp1 and Tp2), the subjects started the stopwatch at the cue of the experimenter and stopped it when they felt that 180 s had passed. In the 600-s time estimation task (Te), the subjects started and stopped the stopwatch on orders from the experimenter when 600 s had actually passed, and subjects then reported how much time they thought had passed. The 600-s time task was taken only once between the two 180-s time tasks to investigate the affect on the second time task.

**2.3. Data analysis**

An analysis of variance (ANOVA) was computed for each dependent variable: time performance, EEG (alpha wave band power ratio), amplitude, latency and response time of P300, SDPTG and subjective assessment.

All the conditions were divided into three groups: the red light, green light and blue I light conditions were analyzed in illuminance, which was approximately 36 lx; the red light and blue II light conditions were analyzed in irradiance, which was approximately 23 μWcm⁻². The last pair was the blue I light and blue II light conditions, which were from the same light source; however, the power of the blue II light condition was half that of the blue I light condition.

**Time task performance:** A two-way repeated-measure ANOVA (color (color groups) × order (Tp1 and Tp2)) was used in the 180-s time task performance, and a one-way repeated measure ANOVA (color groups) was used in the 600-s time task performance.

**EEG:** A two-way repeated-measure ANOVA (color×time) was used in the average values of deviation from baseline condition in the three color groups at Fz, C3, Cz and C4. The time factor means the time of light exposure measured in 15~17 min, 30~32 min and 58~60 min.

**P300:** A two-way repeated-measure ANOVA (color×time’) was conducted in the three color groups. The time’ factor means the time of light exposure measured at the baseline condition and one hour later when the experiment started. A one way repeated measure ANOVA (color in one hour later exposure conditions) was used in the red, green and blue I group, and a paired t-test was used in the red, blue II group and in the blue I, blue II group to analyze the color effects.

**SDPTG:** A one-way repeated-measure ANOVA (color in one hour later exposure conditions) was used in the red, green and blue I group, and a paired t-test was used in the red, blue II group and in the blue I, blue II group. A one-way repeated-measure ANOVA (color×time’) was conducted in three color groups on subjective arousal level, fatigue, stress, eyestrain and the concentration. A one-way repeated-measure ANOVA (color in one hour later exposure conditions) was used in the red, green and blue I group, and a paired t-test was used in the red, blue II group and in the blue I, blue II group to analyze the color effects.

**Subjective assessments:** A two-way repeated-measure ANOVA (color×time’) was conducted in three color groups on subjective arousal level, fatigue, stress, eyestrain and the concentration. A one-way repeated-measure ANOVA (color in one hour later exposure conditions) was used in the red, green and blue I group, and a paired t-test was used in the red, blue II group and in the blue I, blue II group.

When a significant F value was found, we performed a Bonferroni test as a post hoc test. The level of statistical significance was set at 0.05, and the level of statistical significant trend was set at 0.1.
3. Results

Behavioral performance data

Figures 3 and 4 show the 180-s and the 600-s time intervals average values. The mean±S.D. for the red-light condition in Tp1 was 190.90±18.3 s, and that in Tp2 was 184.28±20.29 s. The mean±S.D. for the green-light condition in Tp1 was 219.73±31.06 s, and that in Tp2 was 201.91±17.28 s. The mean±S.D. for the blue I-light condition in Tp1 was 222.04±21.28 s, and that in Tp2 was 192.86±14.67 s. The mean±S.D. for the blue II-light condition in Tp1 was 205.35±19.85 s, and that in Tp2 was 188.91±17.95 s. In the Te task, the mean±S.D. for the red-light condition was 611.50±193.76 s; that for the green-light condition was 618.50±163.16 s; that for the blue I-light condition was 541.17±177.87 s; and that for the blue II-light condition was 548.50±156.26 s.

In the 180-s time task, both main effects were significant, and no interaction was found. The second 180-s time task (Tp2), which was finished after the 600-s time task was significantly shorter than the first one (Tp1) in all four light conditions (in the red, green, blue I group, p=0.028; in the red, blue II group, p=0.029; and in the blue I, blue II group, p=0.012). The time interval for the red light condition was significantly shorter than that for the blue II light condition (p=0.001), and that for the green (p=0.027) and blue I (p=0.031) conditions. In the 600-s time task, the indicated time was a significantly longer in the green light condition compared with the blue I light condition (p=0.015), and the red light condition tended to be significantly longer than the blue I (p=0.05) and blue II light conditions (p=0.057).

In the P300 response times, the time main effects were significantly different (p<0.05) in the red, green, blue I group (p=0.02) and the red, blue II group (p=0.001). The difference between the red and blue II light condition after one hour light exposure showed a significant trend (p=0.067) (Figure 5).

Electrophysiological data

P300: The grand averaged P300 event-related potentials obtained at C4 in all four color light conditions after light exposure are shown in Figure 6. We analyzed the results in amplitudes and latencies of the P300 component.

The amplitude became significantly smaller after the light exposure than the baseline measurements without the color factor in the red, green, blue I group (Fz, p=0.037; C3, p=0.061; Cz, p=0.016; C4, p=0.047) (Cz in Figure 7). There was a significantly trend in the red and blue II light conditions group at C4 for the amplitudes in Blue II tended to be larger than in the red light conditions after one hour of light exposure (p=0.063) (Figure 8). Also at C4, the amplitudes in Blue II light condition tended to be larger than those in Blue I light condition (p=0.093).

The latency became significantly longer after the
light exposure without the color factor in the red, green, blue I light conditions (Fz, p=0.019; C3, p=0.015; Cz, p=0.047; C4, p=0.047) (Cz in Figure 9). At Fz the latency tended to be significantly longer after the light exposure in the red, blue II light conditions group (p=0.05), and the latency also tended to be significantly longer after the light exposure in the blue I and blue II light conditions group (Fz, p=0.082; Cz, p=0.097; C4, p=0.073). However, no significant difference was found among the color light conditions.

**EEG:** The results of determining the EEG alpha wave band power ratio show that the relative values to the baseline conditions significantly decreased in the blue I light condition compared with the green light condition at C3 in the red, green, blue I group (p=0.047) (Figure 10). The relative values significantly increased in the blue II compared with the blue I light condition in the blue I, blue II group (Fz, p=0.036; C3, p=0.074; Cz, p=0.024) (Figure 11).

**SDPTG:** As shown in Figure 12, the -b/a ratio of SDPTG in the blue I light condition tended to be significantly more than that in the green light condition in the red, green, blue I group (p=0.057). The ratio in the blue I light condition tended to be significantly faster than that in the blue II condition in the blue I, blue II group (p=0.085).

**Subjective assessments:** The feelings of arousal level, fatigue and concentration measured by VAS were significantly lower after light exposure without a color effect. The feeling of light brightness in each condition had no significance relationship with color effect. However, regarding eyestrain, we found the relative
values were significantly larger in the red light condition than in the blue II light condition (p=0.049) (Figure 13). This result means the subjects felt more eyestrain in the blue II light condition than in the red light condition. In the investigation to determine the favorite light condition, four subjects chose the green condition and two subjects chose the blue condition. In the investigation to determine for the longest and shortest length of time-past feeling for each light condition, the results were evenly divided among the three colors.

4. Discussion

Color generally is categorized as being either warm (e.g., red, orange, yellow) or cool (e.g., blue, green). Studies have shown that warm colors are psychologically and physiologically arousing and sometimes stressful, whereas cool colors are relaxing and tend to decrease feelings of stress (e.g., Bellizzi et al. 1983). These effects have been found to persist over 10- to 15-minute time periods (e.g., Jacobs and Suess 1975). Moreover, it has been observed that the passage of time tends to be overestimated in a room painted with warm colors and underestimated in a cool-colored room (National Aeronautics and Space Administration, Johnson Spacecraft Center 1976). In the present study, we got the same results that the red or warm color could make the time sense run faster than the time sense with cool color conditions. We found in both 180-s task Tp1 and Tp2 that red light condition was significantly shorter than the green, blue I and blue II conditions. This result showed that the 180-s production time intervals feel faster-passing in the red light condition than in the other color conditions. Katsuura et al. (2005) found the same result that the subjective time sense runs faster in the red light condition than in the blue light condition. However, an interesting finding in the present study was that this effect was attenuated in the 600-s time estimation task, because the time sense in the red light condition came to show a marginally significant difference from the other color conditions. The alteration of significance between the 180-s time task and the 600-s time task may show that the red light condition has an acceleration effect on the time sense, but that it also has a timing characteristic that may be more effective in the short term in our brain, and alter to be normal with time.

In neuroscience study, the basal ganglia have been shown to have an exclusive role in temporal processing, and an additional role of the basal ganglia might be to monitor activity in thalamo-cortico-striatal circuits, where it seems to act as a coincidence detector that signals particular patterns of activity in working memory (Lustig et al., 2005). In this striatal beat-frequency (SBF) model, timing is based on the coincidental activation of medium spiny neurons in the basal ganglia by cortical neural oscillators to permit time comparisons (Matell and Meck 2000). In the present study, the results of the Tp2 180-s time task were significantly shorter than those of the Tp1 180-s time task which was administered before the 600-s time task without color effects. This difference indicated that the time sense run faster when a relatively longer time interval passed as a short working memory effect.

Morita et al. (2005) studied the effects of the menstrual cycle on the time sense and found that the produced times for the 1- to 60-s time-production tests were shorter in the luteal phase than in the follicular phase. In another study, Morita et al. (2007) found that the estimated durations of the given time intervals were higher after previous exposure to 6 h of bright rather than dim light in the morning. These findings are discussed in terms of different load errors (difference between the actual core temperature and its thermoregulatory set-point). According to Delay and Richardson (1980), increasing light levels for 10 min under conditions of dark (less than 0.33 lx), low (80 lx) or high (170 lx) light exposure led to a decrease in time taken to produce a 15-s time interval in women. This result also shows that the subjective estimates of time run...
faster as light levels become higher. However, Aschoff and Daan (1997) found that production of short intervals (10 to 120 s) was increased under higher light intensity, indicating that subjective time runs slower under higher light intensities. These differences show that the light intensity is a very important factor affecting the time sense.

In the present study, we regulated the light intensities as illuminance and irradiance to verify the light intensity effect. The results show that the subjective production time was not affected in the different light intensities, but only in the color effects that were used in the present study. The famous hypothesis about time perception known as the pacemaker-accumulator model has held sway since it was proposed in the 1970s, but it is being challenged now. In the 1990s, researchers proposed that the brain’s stopwatch was located in the basal ganglia, comprising dopamine-secreting “pacemaker” neurons in the substantia nigra and “accumulator” neurons in the striatum (Russell, 2006). Recently, researchers are increasingly convinced that the brain judges intervals on short time scales — milliseconds to minutes and hours — with the help of a distributed network of neurons. This shift is being driven by a slew of findings from electrophysiological studies on animals, behavioral experiments involving patients with brain lesions (Parkinson’s disease) and neuroimaging studies of healthy people. Researchers have also observed that a subset of these regions — including certain areas of the cortex and the striatum — showed higher activity when subjects estimated longer duration than was correct. This assessment of a causal relationship for time estimation may be more complicated under a distributed network.

The P300 results of the response times, amplitudes and latencies show that the performance of P300 was profoundly influenced by the light intensity. The results of the response times show that the blue II light condition tends to be significantly shorter than the red light condition (Figure 5), and the amplitudes of the blue II light condition tend to be significantly larger than those of the red light condition (Figure 7) and larger than those of the blue I condition, although the light intensity of red, blue I conditions was larger than that of the blue II condition. These results indicated that the P300, which is considered a manifestation of cognitive activity, is susceptible to the light intensity effect and may have an inverted U-shaped effect between the light intensity and the cognitive levels or arousal states.

Lockley et al. (2006) assessed the wavelength-dependent sensitivity of acute effects of ocular light exposure on waking EEG. They found that short-wavelength sensitivity to the acute alerting effects of light. The frequency-specific changes in the waking EEG indicate that short-wavelength light is a powerful agent that immediately attenuates the negative effects of both homeostatic sleep pressure and the circadian drive for sleep on alertness, performance and the ability to sustain attention. Lee et al. (2008) found that the AAC (alpha attenuation coefficient) response under different monochromatic light exposures was apparently higher at the 458-nm wavelength than at the other wavelengths. Badia et al. (1991) reported that the alertness measured by EEG beta activity, was greater under bright light condition than dim light condition, and nighttime performance on behavioral tasks was also generally better. In the present study, we found that the EEG alpha band amplitude decreased more from its pre-stimulus values in the blue I light condition than in the green light condition (Figure 8), and the relative values were significantly decreased in the blue I light condition compared to the blue II light condition (Figure 9). These results suggest that the blue light could raise the arousal level of the cortex more than the other colors, and the effect is increased in conjunction with the light intensity. Similar results from the SDPTG show that the blue light might have a sympathomimetic effect and this effect increases along with the light intensity.

5. Conclusions

In the present study, we compared the time sense under different monochromatic lights and found that the color effect had a meaningful connection with the time sense as demonstrated by the finding that the red color had an acceleration effect that changed to normal with the passage of more time. Light intensity change could be covered by the color effect in a narrow range like the condition in the present study. The P300, however, is affected more in the light intensity and may have an inverted U-shaped effect between the light intensity and the cognitive levels or arousal states. The EEG results show that the cortex response increased in the blue color condition and became increasingly active with the light intensity.

In both people and animals, the brain’s ability to keep track of intervals is fundamental to innumerable behaviors and the lighting will be one of the most important factors affecting time perception. In the seconds-minutes range, an activated brain network is involved. The operation of this network can be better understood in terms of various brain areas, as these areas are not limited to temporal processing, but are also involved in other processes. A crucial issue is to differentiate the roles of light intensity and the light coloring in temporal cognition, for example, drawing a relationship diagram between the light intensity and the time sense in different types of monochromatic lighting.
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