Effects of monochromatic light on time perception and muscular performance

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EFFECTS OF MONOCHROMATIC LIGHT ON TIME PERCEPTION AND MUSCULAR PERFORMANCE

A dissertation for the degree of
Doctor of Philosophy (Ph.D.) in Physiological Anthropology
by

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This paper is constituted by the following original papers.

I
Jing-Shi HUANG, Yoshihiro SHIMOMURA, Tetsuo KATSUURA
Effects of Monochromatic Light on Muscle Fatigue and Its Recovery
Journal of the Human-Environment System Vol. 16 No. 1, 2013

II
Jing-Shi HUANG, Yoshihiro SHIMOMURA, Tetsuo KATSUURA
Effects of Monochromatic Light on Different Time Perception
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Preface

This is my doctor thesis project, which is the last part of my doctor study in Humanomics Laboratory, at Chiba University, Japan. Hereby I would like to express my deepest gratitude and respect to my supervisors, Professor Haruo Hibino and Hirohisa Yaguchi, especially to my advising professors, Tetsuo Katsuura, Koichi Iwanaga and Yoshihiro Shimomura. I have always benefited from you expertise supervision, brilliant ideas, continuous enthusiasm, rigorous attitude to science, valuable advice and extensive knowledge. Furthermore, I would also like to give my thanks to my family and friends.

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Chapter 1

General Introduction

1.1. Brief

Living organisms receive a variety of influences from light and the human is no exception. Light is indispensable for leading a complete life.

For thousands of years, people relied mainly on daylight and fire (bonfire, torches, candles and oil). The fundamentals of lighting at that time were related to the quantity of light that was to provide light for people to see and cope in the visual environment also during the dark hours. The use of electrical lighting, even in the industrialized world, is quite recent. Electrical lighting began to spread widely with the development and use of the incandescent lamps. The use of incandescent lamp reached a large scale at the beginning of the 20th century. Powerful lamps such as fluorescent lamps came to the market in the 1950s with the following introduction of high-intensity discharge lamps. Moving from incandescent light sources to discharge light sources raised the issue of color rendering and color temperature. Today, Light emitting diodes (LEDs) are entering the lighting market and as new light sources they enable new approaches to lighting design and practice. LEDs introduce new possibilities for tuning the color of light.

Today, the development of light sources and lighting equipment provides both opportunities and challenges for the lighting design in providing lighting that is not only adequate in terms of quantity, but also meets the lighting quality demands.

Lighting environment directly affects the human-living quality (Katsuura, 2000). Visual comfort is also highly dependent on the application, for example lighting that is considered comfortable in an entertainment setting may be disliked and regarded as uncomfortable in a working space (Boyce 2003). Lighting quality is much more than just providing an appropriate quantity of light. Other factors that are potential contributors to lighting quality include e.g. illuminance uniformity, luminance distributions, light color characteristics and glare (Veitch and Newsham, 1998).

There are many physical and physiological factors that can influence the perception of lighting quality. Lighting quality can not be expressed simply in terms of photometric measures nor can there be a single universally applicable recipe for good quality lighting. Light quality can be judged according to the level of visual comfort and performance required for our activities. This is the visual aspect. It can also be assessed on the basis of the pleasantness of the visual environment and its adaptation to the type of room and activity. This is the psychological aspect. Or non visual aspects related to the effects of light on the human circadian system (Brainard et al. 2001, Cajochen et al. 2005).

With the detection in 2002 of a novel photoreceptor cell in the eye, the biological effects that light has can be better understood. From the research on the biological effects of lighting, it is evident that the rules governing the design of good and healthy lighting installations are, to a certain degree, different from the conventionally held rules. We demonstrate that it can be beneficial to be able to adapt both the level and the color of the lighting. Not only the light on the visual task, but also that entering the eye determines the overall quality of lighting. In a working environment, not only are the advantages in terms of health and wellbeing important for the workers themselves, they also lead to better work performance, fewer errors, better safety, and lower absenteeism (Van Bommel and Van den Beld, 2004).

Thus, in this chapter, I would like to give an outline of the color vision system and the non-vision system. And introduce some background research on physiological and psychological effects of color light.

1.2. Color vision system

Color is different wavelength light absorbed by the eyes, then converted by brain into a feeling that we can perceive. How to describe color? We could perceive color just as we perceive taste. When we eat, our taste buds sense four attributes: sweet, salty, sour and bitter. Similarly, when we look at a scene, our visual nerves register color in terms of the attributes of color: the amount of red; the amount of green; the amount of blue; the amount of yellow etc. and the brightness, to see how colors are registered in terms of the attributes of color.

Color is the byproduct of the spectrum of light (Figure 1-1), as it is reflected or absorbed, as received by the human eye and processed by the human brain.

When light hits objects, some of the wavelengths are absorbed and some are reflected, depending on the materials in the object. The reflected wavelengths are what we perceive as the object's color.

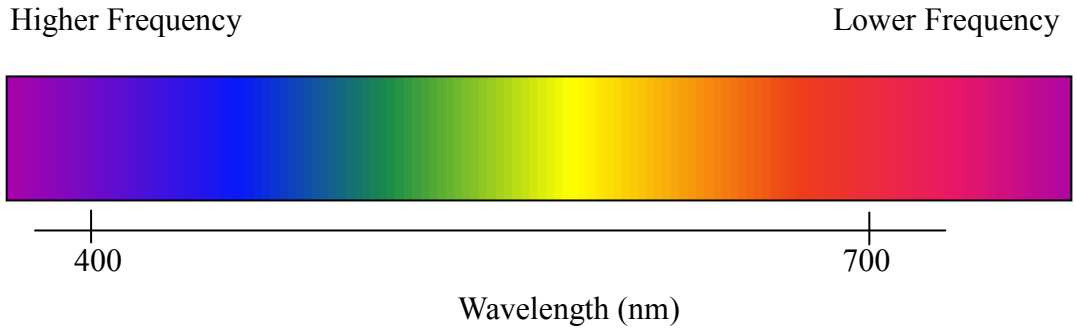

Figure 1-1. Light spectrum.

The visual effects of lighting have been studied for more than 500 years. At the beginning of the 16th century, as regards the mechanism of vision system, Van Leeuwenhoek noted the presence of 'rod and cone cells' in the retina. One hundred years later, the existence of these cells was confirmed as the light sensitive photoreceptors by a German named Gottfried Treviranus in 1834. This discovery opened the way to understand the mechanism of color vision system and conduct research on the visual effects of lighting to design more effective, comfortable lighting environment.

Our eyes are the input channels. The cones and the rods as the photoreceptors regulate the visual effects. When light reaches these cells, a complex chemical reaction occurs. The chemical that is formed (activated rhodopsin) creates electrical impulses in the

nerve that connects the photoreceptor cells with the back of the brain (visual cortex). In the visual cortex of the brain the electrical impulses are interpreted as ‘vision’.

The rods operate in extremely low-level light situations (scotopic vision) and do not permit color vision, which record brightness and darkness and form which we "see" a sort of coarse sketch of the world. The cone system is responsible for sharpness and detail and color vision. For all indoor lighting situations, the cones are decisive factors to a very large extent. The sensitivity of the cone and rod systems varies with varying wavelength of light, thus with varying color of light. There are three types of cones, each one optimized to absorb a different spectrum range of visible light. One set of cones absorbs long wavelengths, the reds called L-cones. Another absorbs mid-size wavelengths, the greens called M-cones. The third absorbs short wavelengths, the blues called S-cones. Together, these rods and cones gather the information that our brains need to combine into one complete image.

For more than 150 years, rods and cones have been considered the only photoreceptors of the mammalian eye. In the past decade, however, evidence has been mounting for the existence of another ocular photoreceptors. A flurry of recent reports has now established the identity of these novel retinal photoreceptors and has begun to delineate their photochemistry, anatomy, functional attributes and roles in behavior. It absorbs wavelength between the S-cones and the M-cones on the spectrum. Up to date it has been known that this novel intrinsic photosensitivity of ganglion cells innervating the circadian pacemaker. More characteristics of this novel photoreceptor wait for our investigation. The detail feature of this new retinal ganglion cells will be discussed in the next part.

Based on the animal experiments, we have known the early part of the primate visual system contains three parallel pathways: the magnocellular, the parvocellular, and the koniocellular streams. The functional significance of these three streams is not fully understood. Research has been focused mainly on the distinction between the magno- and parvocellular systems and it is only relatively recently that attention has been given to the koniocellular system.

Visual information is then sent to the brain from retinal ganglion cells via the optic nerve to the optic chiasma: a point where the two optic nerves meet and information from the temporal (contralateral) visual field crosses to the other side of the brain. After the optic chiasma the visual tracts are referred to as the optic tracts, which enter the thalamus to synapse at the lateral geniculate nucleus (LGN). The lateral geniculate nucleus (LGN) is divided into laminae (zones), of which there are three types: the M-laminae, consisting primarily of M-cells, the P-laminae, consisting primarily of

P-cells, and the koniocellular laminae. M- and P-cells received relatively balanced input from both L- and M-cones throughout most of the retina, although this seems not to be the case at the fovea, where midget cells synapsing in the P-laminae. The koniocellular laminae receive axons from the small bi-stratified ganglion cells.

The cells of the magnocellular and parvocellular layers project all the way to the back of the brain to primary visual cortex (V1). Cells in V1 are arranged in several ways that allow the visual system to calculate where objects are in space. The ability to discriminate lines and edges is improving in primary visual cortex, cells in secondary visual cortex, V2, are refining their ability to interpret colors. V2 is largely responsible for the phenomenon of color constancy, which explains the fact that a red rose still looks red to us under many different colors of illumination. Color constancy is thought to occur because V2 can compare an object and the ambient illumination, and can subtract out the estimated illumination color; however, this process is strongly influenced by what color the viewer expects the object to be. In fact, almost all higher order features of vision are influenced by expectations based on past experience. This characteristic extends to color and form perception in V3 and V4.

Anatomical studies have shown that neurons in extended V4 provide input to the inferior temporal lobe. IT cortex is thought to integrate color information with shape and form, although it has been difficult to define the appropriate criteria for this claim. Despite this murkiness, it has been useful to characterize this pathway (V1 > V2 > V4 > IT) as the ventral stream or the "what pathway", distinguished from the dorsal stream ("where pathway") (Figure 1-2) that is thought to analyze motion, among many other features.

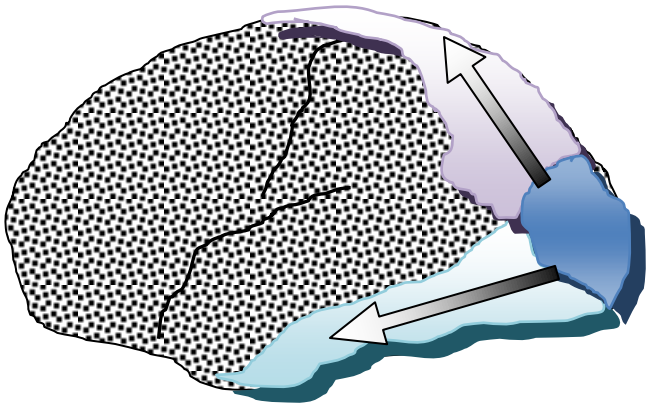

Figure 1-2. Image showing dorsal stream (purple) and ventral stream (light blue) in the human brain visual system.

1.3. Non-vision system

Light is necessary for vision, however, does not only provide visual information but also constitutes a powerful modulator of non-visual functions including improvement of alertness and performance on several cognitive tasks (Brainard and Hanifin, 2005; Berson, 2003). Until recently the brain mechanisms involved in the non-visual effects of light were largely unknown.

Many behavioral and physiological functions, such as sleep-wake regulation, hormone secretion and thermoregulation, vary across the day–night cycle and these rhythms persist with a near 24-h (circadian) period in the absence of time-of-day information (Czeisler and Dijk, 2001; Dijk and von Schantz, 2005). Circadian rhythms are driven by endogenous circadian clocks, the physiological correlates and molecular machinery of which have been described in some detail (Takahashi, 2008). Animal and human studies have established that the daily light–dark cycle is the primary environmental signal that synchronizes endogenous circadian rhythms to the rotation of the Earth. A change in the timing of the light–dark cycle (e.g. a nocturnal light exposure) will result in a shift in the phase of circadian rhythms (Czeisler and Dijk, 2001). This phase-shifting effect of light can only be detected in the longer term (i.e. in the next circadian cycle), but the effects of light are not limited to these long-term effects. Effects of light on (circadian) physiology can be observed during or immediately after the light exposure. They have been reported for many physiological processes such as hormone secretion, heart rate, sleep propensity, alertness, body temperature, retinal neurophysiology, pupillary constriction and gene expression (Czeisler and Dijk, 2001; Dijk and von Schantz, 2005; Dijk and Archer, 2009; Lavoie et al., 2003; Hankins et al., 2008). Although the acute effects of light were first studied using bright light, it has emerged that they can be elicited by ordinary room light or even dimmer light (Zeitzer et al, 2000; Wright et al., 2001; Cajochen et al., 2000). The long term and acute effects of light on (circadian) physiology are referred to as non-visual (or Non-Image Forming - NIF) effects of light because they are not directly related to vision and because they present several features that distinguish them from the visual system (Foster, 2005).

To mediate the non-visual effects of light, lately many research indicated there is a non-classical photoreception system existed. Several evidence demonstrate that the non-visual effects of light are in part mediated by a retinal photoreceptor system distinct from the rods and cones. In some totally blind people and in blind rodents light exposure can induce acute and long-term non-visual responses (Foster, 2005; Czeisler et al., 1995; Zaidi et al., 2007). Furthermore, studies using monochromatic light exposures

in humans, macaques and rodents have demonstrated that non-visual responses are maximally sensitive to blue light (between 459 and 483 nm). This blue light sensitivity is at odds with the spectral sensitivity of classical photoreceptors responsible for vision, which is maximal for green light (~550 nm). In fact, human studies contrasting blue and green exposures have established greater responses to blue light for many variables including changes in the timing of the rhythm of melatonin, acute suppression of melatonin secretion, elevation of body temperature and heart rate, reduction of subjective sleepiness and improvement of alertness. All these observations point to the existence of a non-classical photoreception system that mediates the non-visual effects of light.

We now know that the photo pigment melanopsin plays a key role in mediating these non-visual effects. And the melanopsin renders a small subset of retinal ganglion cells intrinsically photosensitive (ipRGC) with a maximal sensitivity to blue light (~480 nm) (Hankins et al., 2008; Berson et al., 2002). The efferent projections of the ipRGCs include multiple hypothalamic, thalamic, striatal, brainstem and limbic structures (Figure 1-5, 1-6) but the functional significance of most of these projections has not been elucidated. The brain areas that may be involved in the non-visual effect of light beyond these ipRGC projections are also unknown. Nevertheless, if we only consider the number of brain areas that are just one synapse away from ipRGCs, and the numerous projections of just one key target of ipRGCs, the suprachiasmatic nucleus (SCN) of the hypothalamus, site of the principal circadian clock (Saper et al., 2005), it becomes evident that non-visual responses to light could affect not only autonomic nerve system, hormonal secretion, but also many brain functions, including cognitive functions, emotion.

1.4. Previous studies on physiological and psychological effects of color light

Environmental stimuli can affect mood and change physiological response. There is a large number of literatures on the physiology and psychology of color. However, the impact of color in some area of physiology and psychology is still controversial. Color stimuli are characterized completely in terms of hue (i.e., wavelength), brightness or value (i.e., black-to-white quality) and saturation or chroma (i.e., purity or vividness, with lower saturation colors containing more grey). It is usually very difficult, however, to determine the underlying mechanisms contributing to light-induced changes because optical radiation incident on the retina has multiple effects on brain activity through parallel neural pathways. The following sections review concerned studies.

1.4.1. The preview research on color image effects

Every visual stimulus processed by the human perceptual system contains color information. Color is an inseparable part of our everyday lives and its presence is evident in everything that we perceive. It is widely recognized that colors have also a strong impact on our emotions and feelings (Hemphill, 1996). For instance, the color red has been associated with excitement, orange has been perceived as distressing and upsetting, purple as dignified and stately, yellow as cheerful, and blue has been associated with comfort and security (Ballast, 2002). Moreover, some colors may be associated with several different emotions and some emotions are associated with more than one color (Saito, 1996). Red, symbolically known as a dominant and dynamic color, has an exciting and stimulating hue effect. It has both positive and negative impressions such as active, strong, passionate, warm, but on the other hand aggressive, bloody, raging and intense. Green has been found to have a retiring and relaxing effect. It too has both positive and negative impressions such as refreshment, quietness, naturalness, and conversely tiredness and guilt (Davey, 1998, Saito, 1996).

The relationship between color and emotion closely tied to color preferences. In particular, color preferences are associated with whether a color elicits positive or negative feelings. While particular colors have been found to be highly preferred regardless of age, racial group, or culture, there is some evidence that color preference may be culturally-based. For example, Choungourian (1968) found that the colors red and blue were the most preferred colors among American subjects, but were less preferred in other cultures. In a comparision of Japanese and Korean subjects, Saito

(1996) found unique color preference tendencies between the two countries, and also with respect to age, gender, and geographical region within the individual country.

In an investigation of emotional associations with colors, Boyatzis and Varghese (1994) found that light colors (e.g., yellow, blue) are associated with positive emotions (e.g., happy, strong) and dark colors (e.g., black, gray) with negative emotions (e.g., sad, angry). In another study examining color-emotion associations among college students, Hemphill (1996) also found that bright colors elicited mainly positive emotional associations, while dark colors elicited negative emotional associations, results obtained by Boyatzis and Varghese (1994) confirmed this conclusion. However, Saito (1996) found that the color black elicited both negative and positive responses among Japanese subjects, and that black was often a preferred color among young people.

Colors can be described in temperature terms, such as "warm" or "cool" as related to the dominant wavelength of the color. The cool colors (e.g., blue, green, purple) are generally considered to be restful and quiet, while the warm colors (e.g., red, yellow, orange) are seen as active and stimulating (Ballast, 2002). Studies have shown that people exposed to warm colors reported higher levels of anxiety than did people exposed to cool blue and green colors (Kwallek et al., 1988). Bellizzi et al. (1983) showed that warm colors are psychologically and physiologically arousing and sometimes stressful, whereas cool colors are relaxing and tend to decrease feelings of stress.

Color also be indicated having weight. Pinkerton and Humphrey (1974) investigated the apparent heaviness of colors. Five colors (red, orange, yellow, green and blue) were used in their experiment with brightness carefully controlled. The results indicated that red was regarded as the heaviest color, and yellow was regarded as the lightest color. The study did not offer a plausible explanation. Indirect associations, of the kind `red=important=heavy', seem more likely. Red is commonly regarded as a particularly striking color; moreover, in tests of color preferences, red and blue are generally considered the most pleasant colors, yellow the least pleasant. The reasons for color preferences are themselves unclear. Whatever the explanation, the consistency with which people make such peculiar `synaesthetic' judgments about the affective value of colors is remarkable.

Some studies showed that color could affect appetite. The red color stimulates appetite because of its effect on our metabolism, making red a popular color choice among fast-food restaurants. The yellow color is also employed by fast-food moguls to hijack customers' interests – they gain customers' attention, increase their appetite, and encourage them to eat. This is the best way for fast-food companies to generate sales.

By contrast, formal restaurants use blue color to calm and relax their customers. This comforting state is expected to increase the likelihood of the customers lingering longer. Longer stays may correspond to larger meals, more wine, coffee, or desserts, and; therefore, more sales. This is an important strategy for formal restaurants to increase their sales. Although blue is linked to a calm state (Kido, 2000).

There are differences in the perception of colors between genders. Khouw (2002) found that men were more tolerant of gray, white or black than women, and that women reacted to the combinations of red and blue more frequently, and got confused and distracted more than men. It was also found that the combination of red and blue was the most preferred color by adults. These results suggest that there are gender differences in the perception of color. True, the subject's impressions of color seemed to be more subtle and effected not just by the coolness or warmness of the color palette, but also by the calibration of value, chroma, and contrast used in the interiors.

Some research also referred the color image effect to feeling of time. 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). 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. 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. Another research about the interface design (Gorn et al., 2004) investigates the link between the color of a Web page's background screen while the page is downloading and the perceived quickness of the download. Through a series of experiments, they suggest that colors that induce more relaxed feeling states lead to greater perceived quickness.

1.4.2. The preview physiological research on color effects

With the first discussions on the role of light on human health, the lighting quality concept has become more complex, and a change in the way of thinking has occurred. Good lighting should provide for the needed level of visual performance, but it also determines spatial appearance, it provides for safety, and it contributes to wellbeing. Recent studies aimed to find a correlation between environmental lighting and human performance and health, with positive results. What is known, is that insufficient or inappropriate light exposure can disrupt standard human rhythms which may result in adverse consequences for performance, safety, health.

By studying the relationship between human physiology and light, research in photobiology has advanced to the point where some attempts to foresee what the lighting practice will be and need in future are ongoing (Boyce, 2010 and Rea et al., 2002). The idea of designing and using light as a health measure is obviously fascinating, but there are questions to be answered before considering the idea of changing lighting practice. Physiological indices such as neurotransmitters and hormones, and physiological measures of arousal including muscle tension, blood pressure, galvanic skin response, corn temperature, HRV, and brain activities etc. have been measured.

Light information is captured exclusively by the eyes using photoreceptors: rods and cones detect visual information, making the visual system working. The visual system, influenced by the quantity of light available at the retina, is the system that allows the human being to evaluate the surrounding environment, by the perception of the space and the details. In 2001 (Brainard et al. and Thapan et al.), the existence of one more kind of receptor located in the human retina and named “intrinsecally photosensitive Retinal Ganglion cells” (ipRGCs) containing the melanopsin, the photopigment most sensitive to short wavelength radiation (480 nm, blue light), has been discovered. Studies on animals and humans showed that short wavelength radiations stimulate a wide range of physiological responses associated to the neuroendocrine and neurobiological systems, like resetting the timing of the circadian pacemaker, suppressing nocturnal melatonin production, improving alertness (Daurat et al., 1991; Badia et al., 1991; Cajochen et al., 1998, 2000).

On the research of non-visual effects, Vandewalle et al. (2007) investigated the non-visual brain responses, which profoundly influence physiology and behavior. These effects are mediated in part by melanopsin-expressing lightsensitive ganglion cells that, in contrast to the classical photopic system that is maximally sensitive to green light

(550 nm), is very sensitive to blue light (470-480 nm). Using functional magnetic resonance imaging, they indicated that differential modulation regional existed for brain responses. Blue light typically enhanced brain responses or at least prevented the decline otherwise observed following green light exposure in frontal and parietal cortices implicated in working memory, and in the thalamus involved in the modulation of cognition by arousal. The results imply that monochromatic light can affect cognitive functions almost instantaneously and suggest that these effects are mediated by a melanopsin-based photoreceptor system.

Morita and Tokura (1998) discussed the influence of light environment on humans by core temperature and melatonin measure. They proposed in the field of living environment and living engineering that light with a low color temperature should be used for low-level lighting at night, and high-level light with a high color temperature in the morning.

Ueda et al. (2004) used computer monitor to present the color stimuli and recorded the brain activities. The results indicated blue color which compared to white and red could inhibit occipital beta wave, they suggested that blue color may have a sedating effect.

Katsuura et al. (2007) indicated that the time sense ran faster in the red-light than in the blue-light condition. They suggested that the higher activity in the central nervous system that is accounted for by the shorter latency of P300 is related to the acceleration of the time sense.

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.

Langguth et al. (2009) used single and paired-pulse transcranial magnetic stimulation (TMS) to explore the neurobiological mechanisms underlying crossmodal phenomena in 23 men with normal color vision, and in 10 subjects with red–green blindness. Using a sequential challenge, excitability measures were recorded at baseline and during

exposure to either red or green light. Dichromacy did not predict any of the electrophysiological parameters under study regardless of the spectral paradigm. In both dichromats and trichromats, red and green illumination did not induce any significant effects on resting motor threshold, short intracortical inhibition, intracortical facilitation and cortical silent periods. The results suggest that motor cortex excitability as assessed by TMS is not sensitive to the modulatory effects of context-independent red and green light.

Crane et al. (2008) assessed the effect of the color of light in a room on muscular strength and power. Subjects performed a modified Wingate Anaerobic Cycle Test for muscular power and a hand grip strength test in each of the following conditions: red, blue, and white (neutral) ambient light. A repeated-measures multivariate analysis of variance indicated that average muscular power was significantly higher when performing the test in the room with red light compared to rooms lit with blue light or white light. The results also indicated that grip strength was significantly higher in the room lit with white light as compared to the room lit with blue light.

Noguchi and Sakaguchi (1999) investigated how illuminance and color temperature in illumination affect the autonomic nervous system and central nervous system in conditions tending to lower physiological activity, The experimental conditions consisted of 4 conditions provided by a combination of 2 levels of color temperature (3000 K, 5000 K) and 2 levels of illuminance (30 lx, 150 lx). Physiological measurement was carried out during a process of 22 minutes of light exposure followed by 20 minutes of sleep in darkness. They used Heart rate variability (HRV) for an index of the autonomic nervous system, and alpha attenuation coefficient (AAC) and mean frequency of EEG as indices of the central nervous system. Subjective evaluation of drowsiness also carried out. The results suggested that low color temperature light creates a smooth lowering of central nervous system activity, and that low color temperature illumination can be used effectively in a bedroom or other such environment where it is desirable to facilitate lowered physiological activity.

Ishibashi et al. (2007) used two different spectral analyses of heart rate (HR) variability (HRV) on seven young male subjects to evaluate the effects of different color temperatures of light exposure (6700 K, 5000 K, 3000 K) before sleep on cardiac vagal activity. The results showed that suppressions of HR during sleep after 6700 K light exposure were more inhibited than the other two lighting conditions. Increases in high-frequency (HF) components of HRV during sleep were also inhibited by 6700 K pre-sleep lighting. These results indicate that pre-sleep exposure to light of a higher color temperature may inhibit the enhancement of cardiac vagal activity during sleep.

1.5. The purpose of this study

There is little doubt that color greatly affects our subjective experience and there are significant cultural associations to color. Color is a large component of creating conscious experience as well as eliciting unconscious instinctual responses. A large number of research had shown effects of color on mood, physiology, and health.

The purpose of this study is to examine the effects of different monochromatic lights on the time perception and the muscular performance. Unfortunately, most research focused on the melatonin, phase or corn temperature variation, and several put the focus on high illumination light exposure during the night time period, only few studies do the research on arousal level on the daylight.

Aside from anecdotal reports, there is a lack of scientific validation of the efficacy of monochromatic light exposure on time perception and muscle performance by a physiological method. By studying the relationship between human physiology and light, research in photobiology has advanced to the point where some attempts to foresee what the lighting practice will be and needed to be in future are ongoing. The idea of designing and using light as a health measure is obviously fascinating, but there are questions to be answered before considering the idea of changing lighting practice. For example, what kind of wavelength in lighting effectively affects the arousal level? How could the ambient color light change our cognition including time perception? Is the light exposure influence has a time restriction? Will the ambient color light change the muscle strength output? Is the monochromatic light therapy efficient on the muscle fatigue recovery?

Furthermore, previous studies using monochromatic light exposures have demonstrated that non-visual responses are most sensitive to blue light (between 459 and 483 nm). It is necessary to establish the spectral sensitivity characteristic of the physiology reaction to human non-visual effect by monochromatic light for many variables not only including acute suppression of melatonin secretion, elevation of body temperature and heart rate, reduction of subjective sleepiness and improvement of alertness, but also some other physiological responses and behaviors which may be related to a non-classical photoreception system that mediates the non-visual effects of light.

In this paper, we try to discuss the light effects when human subjects are exposed to the monochromatic lights. We investigated the time perception by the time production task in 180 s and 600 s to reveal the connection between interval timing and brain activities. Moreover, we examined the muscular strength output under the different

monochromatic ambient light and the fatigue states and its recovery as a muscular performance.

In order to explain our purpose, the central nervous system was measured by EEG, VEP, P300 and the autonomic nervous system was measured by PPG. And the EMG, MDF for muscular performance. In addition to measuring physiological data, time sense had been assessed by stopwatch, and mood state had also been measured with several brief questionnaires. The effects of monochromatic light were deliberated in this study, and especially to the recent discoveries in photobiology, which can in future have an impact on the way lighting design.

Composition of this paper:

The contents of each chapter which constitutes this doctoral dissertation『Effects of monochromatic light on time perception and muscular performance』are shown below.

Chapter 1「General Introduction」introduced the mechanism of color vision system and non-vision system. Some previous physiological and psychological research is listed for a review.

Chapter 2「The influence of chromatic light on cerebral cortex activity measured by visual evoked potentials」validated the visual evoked potential as a measure method to reflect the difference effects of chromatic light information and demonstrated the relationship between the component of VEP and the local positions.

Chapter 3「The effects of monochromatic light on different time intervals」expounded the physiological response on two different time tasks to demonstrate a hypothesis that red color has an acceleration effect to human perception, however, decreases with the elapse of time.

Chapter 4「The effects of monochromatic light on muscle strength」proposed and tested the prediction that perceiving color affects the force of motor output. And try to sort out the relationship between color effects on muscular strength experiment and the experimental methods.

Chapter 5「The effects of monochromatic light on muscle fatigue recovery」demonstrated the muscular fatigue performance and the recovery from muscle fatigue task and the recovery period measure under the different monochromatic light conditions. And discussed the possibility of color light influence during the processing.

Chapter 6「General discussion」epitomized the contents above. This chapter expatiated on a new theoretical approach for lighting which needs to understand the role

of lighting exposure. It can improve the design of the ambient light environment based on these discoveries.

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Chapter 2

The influence of chromatic light on cerebral cortex activity measured by visual evoked potentials

2.1. Background

According to literature data there are three visual channels transferring the visual information from the retina to the striatum. One of them, the parvocellular (sustained) system, is the form and color oriented channel, the second, magnocellular (transient) one, carries predominantly motion information (Livingstone and Hubel, 1988). The third pathway, koniocellular, was not so thoroughly examined yet and its contribution to visual processing is only partially understood so far (Hendry & Calkins, 1998). The channels are named in accordance with the relay LGN cells belonging to. After entrance of these channels to visual cortex (the primary visual area V1-Brodmann's area 17), they become more mutually interconnected. The magnocellular channel continues to V2, V3A and MT (V5) extrastriate areas as the 'magnocellular pathway' or 'parietal (dorsal) stream' mainly responsible for processing of motion and space information. The parvocellular pathway coming in V2 (temporal-ventral stream) is involved in perception of colors and shapes (Tootell et al., 1998; Ungerleider and Desimone, 1986).

Some studies used comprising motion oriented visual evoked potentials (VEPs) to do the magnocellular (dorsal) pathway examination (Kuba and Kubova´, 1992). Some results showed that a negative component timed at about 160 ms (N1) in the motion-onset visual evoked potentials (MVEPs) displays very high contrast sensitivity (Kubova´ et al., 1995).

A visual evoked potential (VEP) investigation in figure salience by Romani et al, 1999). Their VEP data was related to contour formation in vision, using checkerboard stimuli. They concluded that VEPs contain an early component corresponding to segregation of edges and a later part related to surface 'filling-in'.

Transient VEPs in response to chromatic stimuli are immature in morphology until about puberty which could be used in research during infancy and childhood (Crognale et al., 1998; Crognale, 2002; Pompe et al., 2006). The VEP reflects retino-striate visual pathway function.

VEPs are a common means of investigating cortical mechanisms of vision. To date, most research has used pattern stimulation, while VEP responses as event related potentials to check the later components for processing information about color have been largely ignored.

It is quite important to develop examination technique for an objective selective assessment of the visual pathways function. Thus, the aims of this chapter were to investigate transient VEPs induced by the monochromatic color stimuli to compare the different monochromatic light effects for demonstrating the color information process

associated to each component of VEPs in brain. Finally, the present study focused on investigating the relationship between each component and the local positions.

2.2. Methods

2.2.1. Subjects

Eight subjects (mean age 25 years; range 20-35years) were recruited to the study. Informed consent was obtained before the experiment, VEP chromatic transient stimuli were assessed in all subjects. All subjects were inquired for color vision deficiencies by taken a dictation themselves.

2.2.2. Measurements

2.2.2.1. Experimental circumstance

A darkened room for this study was built in a climatic chamber. The dark room consisted of two parts. One is called signal room which was used to fixed stimuli equipment. The other one is the test room which was made electromagnetic shields for signal noises isolated (Figure 2-1).

Subjects were asked to sit down in a comfortable chair (LEVINO chair KE-627 made by ITOKI) 1 m away ahead of the wall and to hold their gazes straighten. By changing the height of chair make sure all subjects' gazes on the same horizon with the center of light source glass (Φ90 mm) on the wall.

(Temperature 25℃, Humidity 50%)

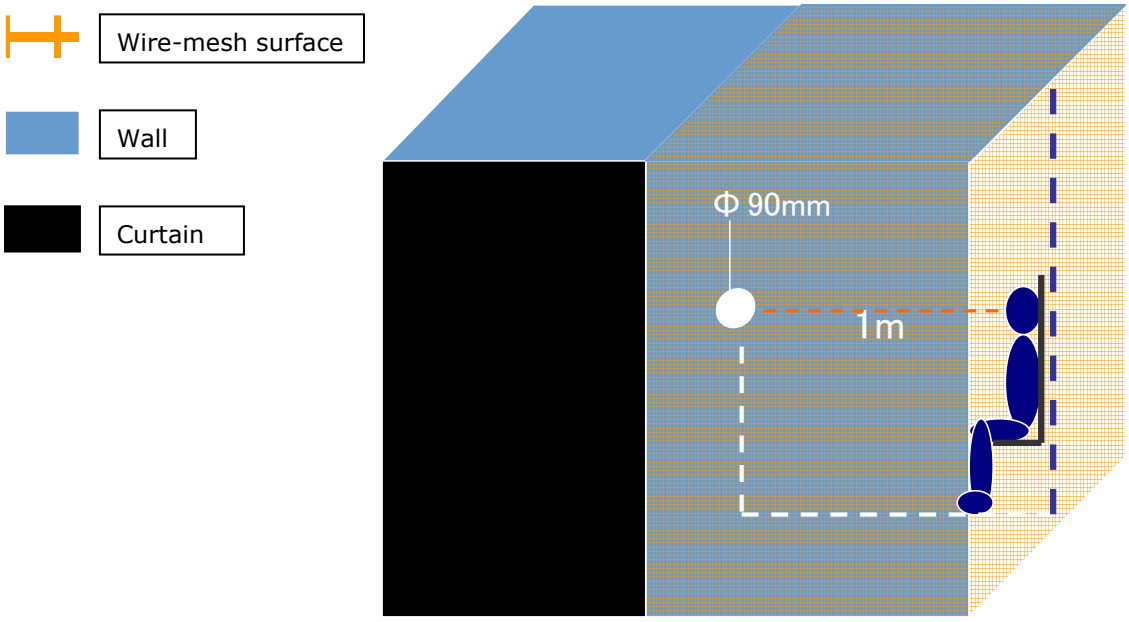


Figure 2-1. The image of experimental circumstance.

2.2.2.2. Equipments

The LED control circuit was shown in Figure 2-2 and the MESL-PC control program was shown in Figure 2-3 supported by TOSHIBA Lighting company.

Light stimuli were set by a time unit like 500ms etc. on the MESL-PC control program which means the minimum system working time on the program. There were three LED (Figure 2-4) connected to the control circuit. And we can make the color show together or alone, working with 100% power or 70%.

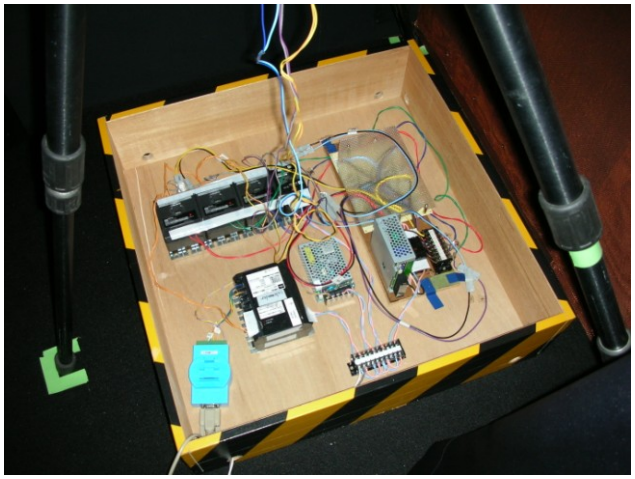


Figure 2-2. The LED control circuit.

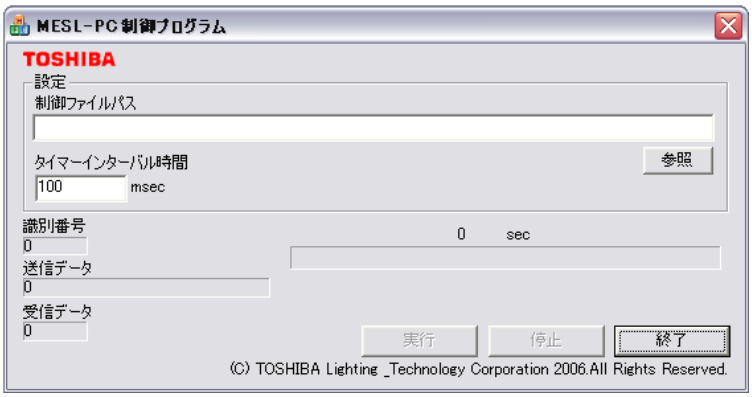


Figure 2-3. The MESL-PC control program. The photodiode sensor feedback a single to computer when the LED it outfitted to lights up.

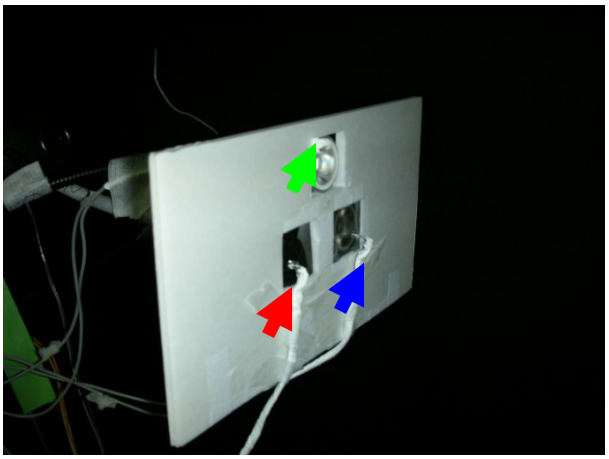


Figure 2-4. The light stimuli sensors by LEDs.

The characteristic of photodiode sensor

It has a closed sensitivity spectrum with the visual sensitivity spectrum (Figure 2-5).

response time < 4ms

λp = 520nm

Work voltage: 1.8V~6.0V.

Work theory:

The analog current output

when illumination is changed.

Figure 2-5. The photodiode sensor.

2.2.2.3. Stimuli

Stimuli were generated from the MESL-PC control program and the LED equipment.

The stimuli used were three circular LED lighting. They were named after the color sensation they produced (We opted representative regions across the visible spectrum for color stimuli. They were Red, Green, and Blue). Before the experiment the irradiance (incident radiant flux density) was regulated by ND filter (Figure 2-6 and Table 2-1) to the value approximated. Then have been presented through an opal light diffusion glass on the wall. The time interval between each stimulus was kept random (ranging between 1.5 and 2.5 s) in order to keep a minimum training effect. The stimulus duration was 500 ms and was presented a simple color once.

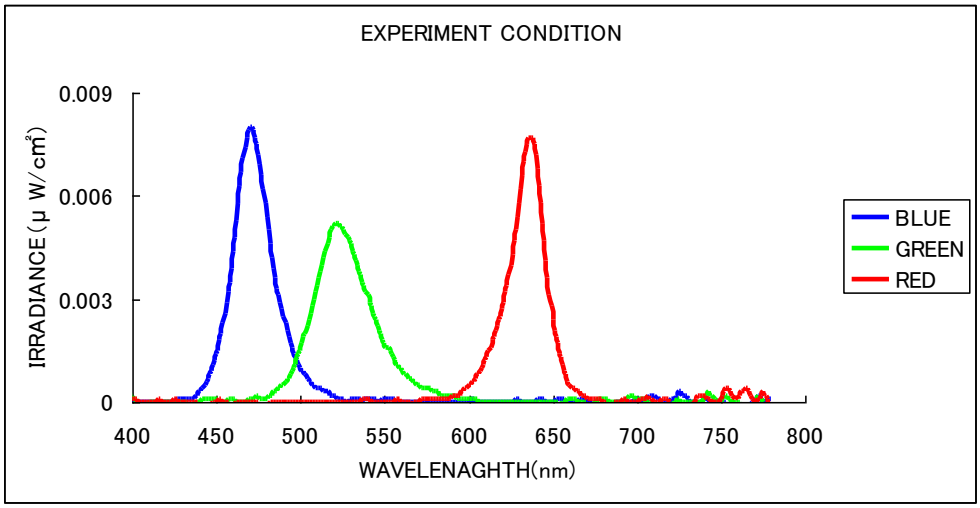


Figure 2-6. The wave-irradiance of three LED stimuli source.

Table 2-1. Parameter of the LED stimuli.

COLOR	WAVELENGTH (nm)	IRRADIANCE (μ Vcm-2)	PHOTOPIC ILLUMINANCE (lx)	SCOTOPIC ILLUMINANCE (lx)
RED	637	0.21	0.36	0.01
GREEN	522	0.23	1.12	2.96
BLUE	472	0.24	0.22	2.86

2.2.2.4. Experimental procedures

The subject was requested having a good rest on preceding day for making sure having a good concentration during the experiment. All the experiment times were set in the afternoon between 13:00 to 17:30. Prior to the initiation of the experiment, the electrodes were placed and subjects were asked to remain comfortably seated in a darkened room 1m from the wall, The subject's task was to direct attention to the target spot straightly on the wall. Then stimulation-recording procedure started: At the first five minutes, the subject was asked to make relaxation himself and keep the eyes opened to fit the dark surrounding, and then the stimuli of each color were presented to the subject randomly in three minutes, and then have a rest in three minutes. One session consisted of stimuli and rest all in three minutes, and all sessions amounted to fifteen. The same experiment was conducted twice on a different day, for checking repeatability.

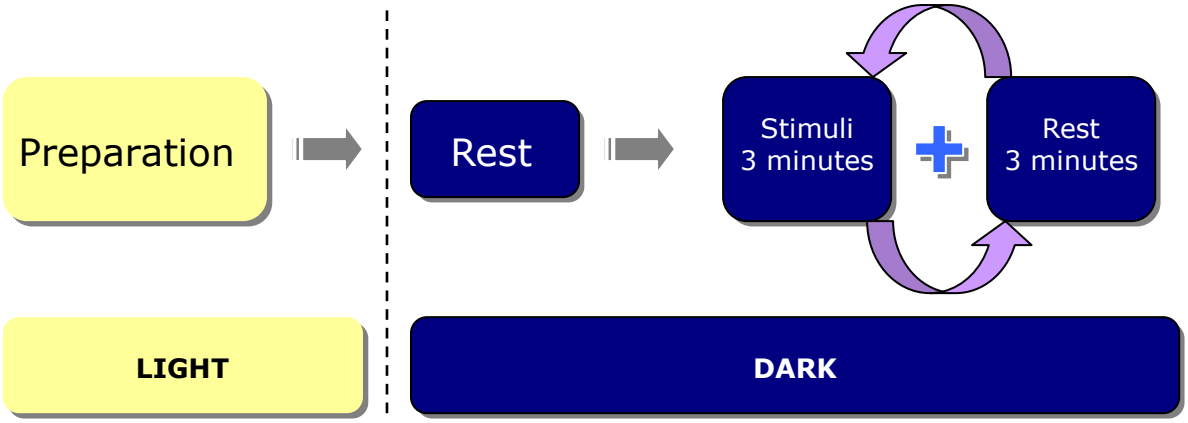


Figure 2-7. The experimental processing.

Twelve surface electrodes were placed over the scalp according to the 10-20 International electrode System. Recording sites were 16 places for active sites (Figure 2-7). Electrode reference was established at A1-A2 (both earlobes linked). Sites were first abraded using alcoholized cotton and 9mm Ag/AgCl electrodes were attached using a commercially available EEG paste. Impedance was sure below 8 kΩ for all recordings. The EEG signals were band-pass filtered from 0.56 to 100Hz. Recording sensitivity was set at 50μV. Two hundred and fifty-six samples were acquired from each trial using a A/D converter (MP150). The sampling time was 256ms (sampling rate: 1000Hz). Before the stimulus onset, EEG activity was recorded for a baseline time of 100ms.

EOG provided for the elimination of eye movement on analysis off-line. (Figure 2-8) The EOG signals were band-pass filtered from 0.032 to 100Hz.

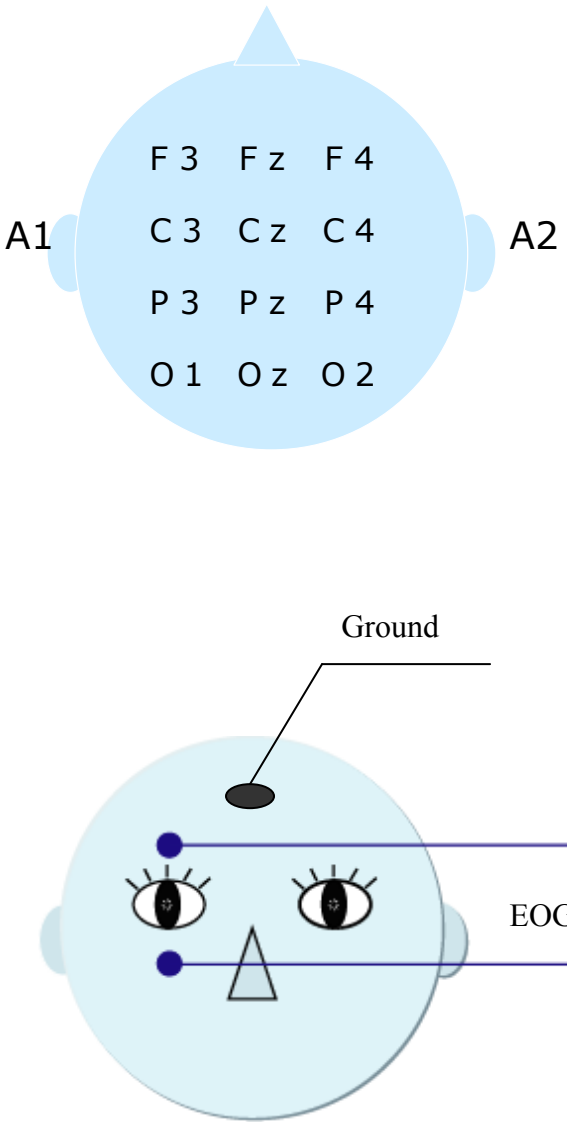


Figure 2-8. Electrodes location by International 10-20 system of EEG and the electrodes of EOG.

2.2.3. Data analysis

As the priority sequence, EOG analysis was performed at first to make sure the portions of VEP recording associated with eye movements were rejected. Secondly, the VEP data was averaged calculation. And then the correlation was gotten by ANOVAs.

Amplitudes (relative to pre-stimulus baseline), and peak latencies of major VEP components were calculated for each subject in the following time window: N1 (45–100ms), P1 (80–140 ms), N2 (130–200 ms), P2 (180–240 ms).

Amplitudes and latencies relative to each time window were separately analyzed with three-way repeated measure ANOVA. The level $p<0.05$ was considered significant. Factors were order of conditions (three levels), rounds (two times: first experiment and second experiment), colors (three levels: red green and blue) and electrode positions (twelve levels: O1, Oz, O2, P3, Pz, P4, C3, Cz, C4, F3, Fz and F4).

For assessing the repeatability, the experiment had been done as the same method as described before, and the criteria component of VEPs were analyzed by reliability analysis scale.

An analysis of variance (ANOVA) was carried out on the response data. In the ANOVA, Mauchly's test of sphericity was used for the target value for analysis. If there was not significant, the more conservative Greenhouse-Geisser or Huynh-Feldt test was used in the analysis. Adjustment for multiple comparisons used in Bonferroni.

Amplitude of P2

As a result of three-way repeated measure ANOVA.

Round × Color × Electrode position

Within-subject effect measure

Analyses of variance for the effect of round, color and electrode position on the VEP amplitude function of P2.

Source of variation	d.f.	Sum of squares	F statistics	P-values
Round	1	75.276	0.894	0.381
Color	2	526.527	3.945	0.088
Electrode position	11	4098.750	8.969	0.000
Round×Color	2	6.892	0.483	9.629
Round× Electrode position	11	65.826	0.943	0.506
Color× Electrode position	22	2059.268	10.858	0.000
Round×Color× Electrode position	22	54.456	1.536	0.073

Table 2-2. The ANOVA showed that there was a significant main effect of the Electrode position, $F(11, 66) = 8.969$, $p<0.001$. Together with significant interactions between the color and electrode position, $F(22, 132) = 10.858$, $p<0.001$.

From three-way repeated measure ANOVA, we had known that rounds were no significant. So we put the data from experiment I and II as a mean to analysis two-way repeated measure ANOVA.

Amplitude of P2 (mean) with Color × Electrode position

Color × Electrode position was significant

$F(22, 154) = 9.560$, $p<0.001$.

Pair comparability

Position	Source of variation	Pair object	SEM	P-values
FL	R	G	3.100	0.039
		B	3.120	0.046
	G	R	3.100	0.039
		B	0.552	1.000
	B	R	3.120	0.046
		G	0.552	1.000
FM	R	G	2.201	0.082
		B	2.017	0.083
	G	R	2.201	0.082
		B	0.406	0.728
	B	R	2.017	0.083
		G	0.406	0.728
FR	R	G	2.688	0.035
		B	2.881	0.048
	G	R	2.688	0.035
		B	0.799	1.000
	B	R	2.881	0.048
		G	0.799	1.000

Table 2-3. Analyses of variance for the effect of electrode positions on the left brain hemisphere on the VEP latency function of P2.

The ANOVA showed that there was a significant main effect of the Electrode position only on the FL, FR against colors.

Latency of P2

As a result of three-way repeated measure ANOVA.

Round × Color × Electrode position

Within-subject effect measure

Source of variation	d.f.	Sum of squares	F statistics	P-values
Round	1	628.907	0.521	0.497
Color	2	1126.552	0.342	0.717
Electrode position	11	30307.308	5.991	0.000
Round×Color	2	34.242	0.050	0.952
Round× Electrode position	11	680.355	1.286	0.252
Color× Electrode position	22	9716.020	4.146	0.000
Round×Color× Electrode position	22	643.567	0.646	0.883

Table 2-4. Analyses of variance for the effect of round, color and electrode position on the VEP latency function of P2.

The ANOVA showed that there was a significant main effect of the Electrode position, $F(11, 66) = 5.991$, $p<0.001$. Together with significant interactions between the color and electrode position, $F(22, 132) = 4.146$, $p<0.001$.

From three-way repeated measure ANOVA, we had known that rounds were no significant. So we put the data from experiment I and II as a mean to analysis two-way repeated measure ANOVA.

Latency of P200 (mean) with Color × Electrode position

Electrode position $F(11, 77) = 6.151$, $p<0.001$ and
Color × Electrode position $F(22, 154) = 2.743$, $p<0.001$ was significantly difference.

For N1 component, it cannot be analyzed in three-way repeated measure ANOVA with rounds, colors and electrode positions, because the early component was not strong

enough for observation in several subjects, and the data which recorded from experiment I and II were not paired several times. So after disposition, we reset the data by cutting unpaired amplitudes and latencies set. And then we put all the data from N1 into three groups named by the electrode positions left, middle and right. At last, we analyzed them inner-group in two-way repeated measure ANOVA with colors and electrode positions.

Amplitude of N1

Amplitude of N1 was no significant on main effect or interaction with colors and electrode positions.

Latency of N1

Color × Electrode position (Left)

Electrode position was significant main effect.
F (3, 9) =64.428, p<0.001.

Pair comparability

Source of variation	Pair object	SEM	P-values
OL	PL	0.854	1
	CL	3.488	0.019
	FL	2.982	0.015
PL	OL	0.854	1
	CL	3.645	0.020
	FL	2.217	0.006
CL	OL	3.488	0.019
	PL	3.645	0.020
	FL	3.888	1
FL	OL	2.983	0.015
	PL	2.217	0.006
	CL	3.888	1

Table 2-5. Analyses of variance for the effect of electrode positions on the left brain hemisphere on the VEP latency function of N1.

The ANOVA showed that there was a significant main effect of the Electrode position, OL-CL, OL-FL, PL-CL, PL-FL, $p<0.001$.

Latency of N1 Color × Electrode position (Middle)
Electrode position was significant main effect.
$F(3, 6) = 151.171$, $p<0.001$.

Pair comparability

Source of variation	Pair object	SEM	P-values
OM	PM	0.553	0.751
	CM	2.342	0.006
	FM	1.755	0.003
PM	OM	0.552	0.751
	CM	2.162	0.004
	FM	1.739	0.003
CM	OM	2.343	0.006
	PM	2.162	0.004
	FM	1.032	1
FM	OM	1.755	0.003
	PM	1.739	0.003
	CM	1.032	1

Table 2-6. Analyses of variance for the effect of electrode positions on the brain parietal on the VEP latency function of N1.

The ANOVA showed that there was a significant main effect of the Electrode position, OM-CM, OM-FM, PM-CM, PM-FM, $p<0.001$.

Latency of N1 Color × Electrode position (Right)
Electrode position was significant main effect.
$F(3, 9) = 70.914$, $p<0.001$.

Pair comparability

Source of variation	Pair object	SEM	P-values
OR	PR	1.581	1
	CR	3.833	0.026
	FR	2.681	0.009
PR	OR	1.581	1
	CR	2.856	0.009
	FR	3.354	0.014
CR	OR	3.833	0.026
	PR	2.856	0.009
	FR	3.351	1
FR	OR	2.682	0.009
	PR	3.354	0.014
	CR	3.351	1

Table 2-7. Analyses of variance for the effect of electrode positions on the right brain hemisphere on the VEP latency function of N1.

The ANOVA showed that there was a significant main effect of the Electrode position, OR-CR, OR-FR, PR-CR, PR-FR, $p<0.001$.

Amplitude of P1 and N2

As the components P1 and N2 were not stronger enough, we put the data into ATAMAP software which charge on the EEG mapping. And use t test for assessing whether the means of chromatic lights are statistically different from each other.

P1 component

Groups	Electrode position	t-values	p-values
RED-GREEN	C3	-3.129	0.020
RED-BLUE	none		
GREEN-BLUE	O1	2.204	0.070
	O2	2.167	0.073

Table 2-8. Analyses of t-test among the pair of RED, GREEN and BLUE for P1 component.

N2 component

Groups	Electrode position	t-values	p-values
RED-GREEN	P3	5.804	0.001
	P4	2.510	0.046
RED-BLUE	O1	2.090	0.082
	O2	2.076	0.083
	P3	4.636	0.004
	P4	3.491	0.013
GREEN-BLUE	O2	2.996	0.024

Table 2-9. Analyses of t-test among the pair of RED, GREEN and BLUE for N2 component.

2.3. Results

Not all the components have been observed from all the subjects in this study. We found almost N1 (45–100ms), all the P2 (180–240 ms) but a few P1 (80–140 ms) and N2 (130–200 ms). In this result, we want to talk about the amplitudes and latencies on N1 and P2. And from the EEG mapping analysis, talk about the inclination meaning about P1 and N2.

2.3.1. The VEP repeatability data

The VEP data from experiment I and II were used intraclass correlation coefficients for repeatability analysis. Because of the imperfection of P1 and N2, we just analysis the early component N1 and the later component P2 to hold the repeatability of the visual evoked potentials.

The intraclass correlation coefficient is a measure of correlation, consistency or conformity for a data set when it has multiple groups. Consider a data set with two groups represented in a data matrix then the intraclass correlation r is computed from formula.

P2 component

Amplitude of P2

Reliability analysis - SCALE (Alpha)

Correlation Matrix

	II	I
II	1.0000	
I	0.8091	1.0000

N of Cases = 286.0

Analysis of Variance

Source of Variation	Sum of Sq.	DF	Mean Square	F	Prob.
Between People	12748.3169	285	44.7309		
Within People	1454.6110	286	5.0861		
Between Measures	48.8329	1	48.8329	9.9001	.0018
Residual	1405.7781	285	4.9326		
Total	14202.9279	571	24.8738		
Grand Mean	7.1698				

Intraclass Correlation Coefficient

One-way random effect model: People Effect Random

Single Measure Intraclass Correlation = 0.7958

95.00% C.I.: Lower = 0.7491 Upper = 0.8347

F = 8.7948 DF = (285, 286.0) Sig. = 0.00 (Test Value = 0.00)

Average Measure Intraclass Correlation = 0.8863

95.00% C.I.: Lower = 0.8565 Upper = 0.9099

F = 8.7948 DF = (285, 286.0) Sig. = 0.00 (Test Value = 0.00)

Reliability Coefficients 2 items

Alpha = 0.8897 Standardized item alpha = 0.8945

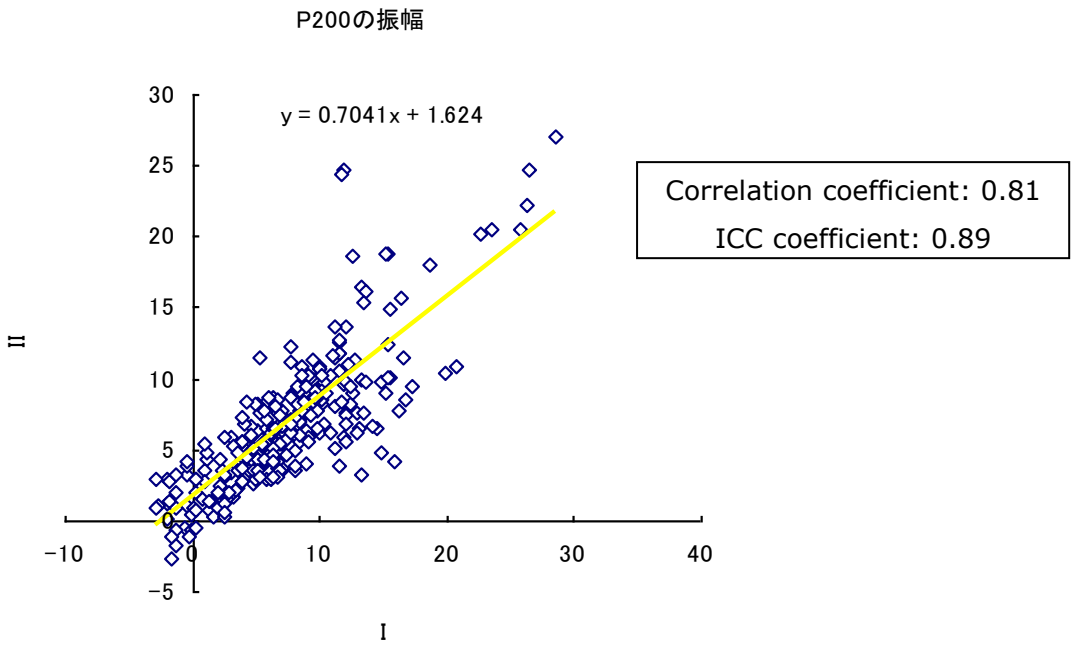


Figure 2-9. The correlativity of Amplitudes on P2.

Latency of P2

Reliability analysis - SCALE (Alpha)

Correlation Matrix

	II	I
II	1.0000	
I	0.7613	1.0000

N of Cases = 286.0

Analysis of Variance

Source of Variation	Sum of Sq.	DF	Mean Square	F	Prob.
Between People	187391.1066	285	657.5127		
Within People	26975.5000	286	94.3199		
Between Measures	177.9038	1	177.9038	1.8921	.1701
Residual	26797.5962	285	94.0267		
Total	214366.6066	571	375.4231		
Grand Mean	214.5647				

Intraclass Correlation Coefficient

One-way random effect model: People Effect Random

Single Measure Intraclass Correlation = 0.7491

95.00% C.I.: Lower = 0.6935 Upper = 0.7958

F = 6.9711 DF = (285, 286.0) Sig. = 0.00 (Test Value = 0.00)

Average Measure Intraclass Correlation = 0.8566

95.00% C.I.: Lower = 0.8190 Upper = 0.8863

F = 6.9711 DF = (285, 286.0) Sig. = 0.00 (Test Value = 0.00)

Reliability Coefficients 2 items

Alpha = 0.8570 Standardized item alpha = 0.8645

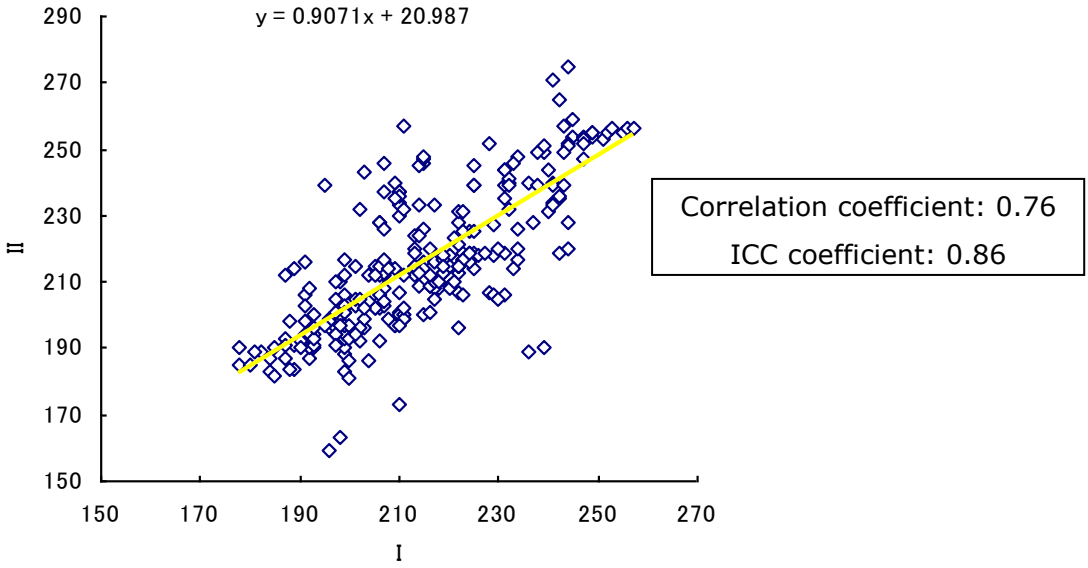


Figure 2-10. The correlativity of Latencies on P2.

N1 component

Amplitude of N1

Reliability analysis - SCALE (Alpha)

Correlation Matrix

	II	I
II	1.0000	
I	0.7486	1.0000

N of Cases = 189.0

Analysis of Variance

Source of Variation	Sum of Sq.	DF	Mean Square	F	Prob.
Between People	904.4217	188	4.8108		
Within People	134.7175	189	.7128		
Between Measures	4.5897	1	4.5897	6.6308	.0108
Residual	130.1279	188	.6922		
Total	1039.1392	377	2.7563		
Grand Mean	-1.2426				

Intraclass Correlation Coefficient

One-way random effect model: People Effect Random
Single Measure Intraclass Correlation = 0.7419
95.00% C.I.: Lower = 0.6704 Upper = 0.7989
F = 6.7492 DF = (188, 189.0) Sig. = 0.00 (Test Value = 0.00)

Average Measure Intraclass Correlation = 0.8518

95.00% C.I.: Lower = 0.8027 Upper = 0.8887
F = 6.7492 DF = (188, 189.0) Sig. = 0.00 (Test Value = 0.00)
Reliability Coefficients 2 items
Alpha = 0.8561 Standardized item alpha = 0.8563

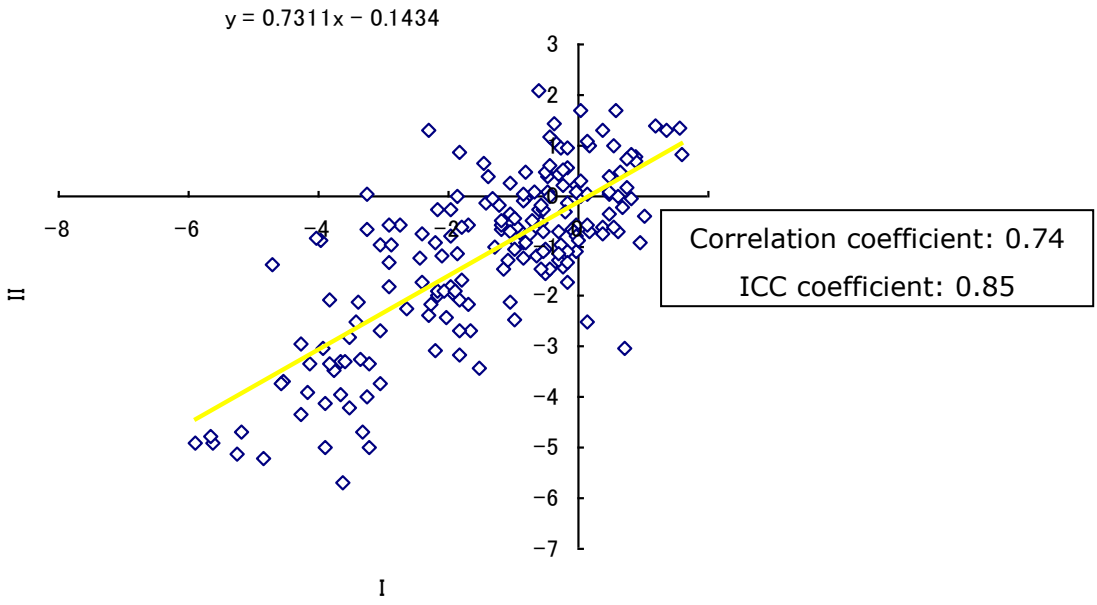


Figure 2-11. The correlativity of Amplitudes on N1.

Latency of N1

Reliability analysis - SCALE (Alpha)

Correlation Matrix

	II	I
II	1.0000	
I	.8722	1.0000

N of Cases = 189.0

Analysis of Variance

Source of Variation	Sum of Sq.	DF	Mean Square	F	Prob.
Between People	92919.0000	188	494.2500		
Within People	7011.0000	189	37.0952		
Between Measures	599.4074	1	599.4074	17.5758	.0000
Residual	6411.5926	188	34.1042		
Total	99930.0000	377	265.0663		
Grand Mean	81.6667				

Intraclass Correlation Coefficient

One-way random effect model: People Effect Random

Single Measure Intraclass Correlation = 0.8604

95.00% C.I.: Lower = 0.8183 Upper = 0.8933

F = 13.3238 DF = (188, 189.0) Sig. = 0.00 (Test Value = 0.00)

Average Measure Intraclass Correlation = 0.9249

95.00% C.I.: Lower = 0.9011 Upper = 0.9436

F = 13.3238 DF = (188, 189.0) Sig. = 0.00 (Test Value = 0.00)

Reliability Coefficients 2 items

Alpha = 0.9310 Standardized item alpha = 0.9317

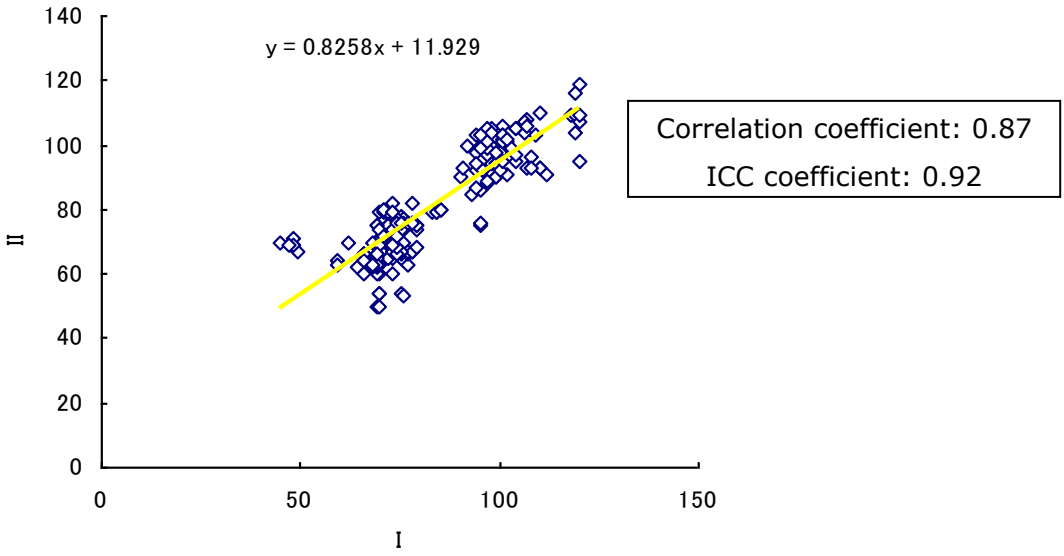


Figure 2-12. The correlativity of Latencies on N1.

The results of VEP repeatability analysis

We used intraclass correlation coefficients for repeatability analysis on experiment I and II.

The factors were amplitudes and latencies from P2 and N1.

Components	factors	Correlation coefficient	ICC coefficient
P200	Amplitude	0.81	0.89
	Latency	0.76	0.86
N72	Amplitude	0.74	0.85
	Latency	0.87	0.92

Table 2-10. The results of four factors from two components on correlation coefficient and ICC coefficient.

The correlation no relations about neither in the factors Amplitude and Latency, nor in the two components P2 and N1 was very significant from experiment I and II by interpreting base on correlation coefficient and ICC coefficient.

2.3.2. Electrophysiological data

The result of P2 and N1 components

The group-averaged transient VEPs recorded from eight subjects, in response to flash chromatic stimulus, were presented in Figure 2-12a and Figure 2-12b. The morphology of the group-averaged transient VEPs consisted of a negative-positive complex, which agrees with past findings.

The peak for P2 was respectively on Fz, and the difference between these means was significant. Although there is not any report between chromatic stimuli on P2 in previous studies.

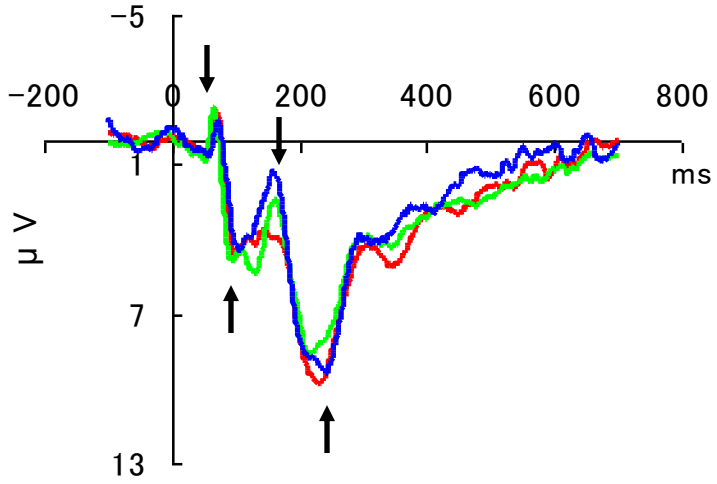


Figure 2-12a. The group-averaged transient VEPs in response to flash chromatic stimulus on Oz. Group n=8.

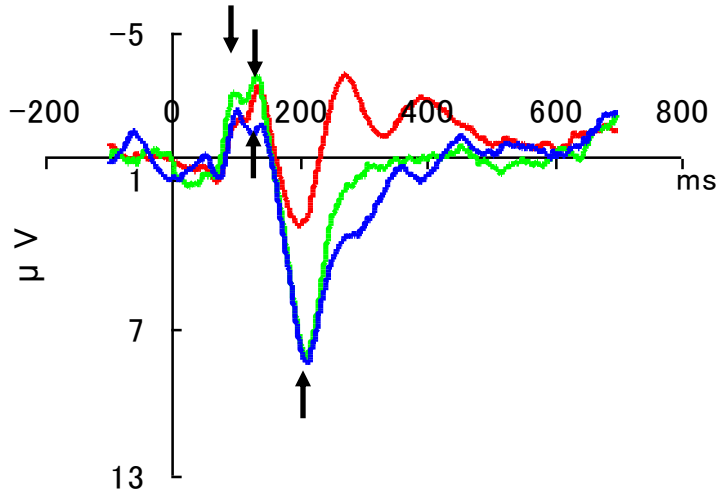


Figure 2-12b. The group-averaged transient VEPs in response to flash chromatic stimulus on Fz. Group n=8.

Noted that in each plot in Figure 2-12, there were several peaks appeared. We named them as the different time windows: N1 (45–100ms), P1 (80–140 ms), N2 (130–200 ms), P2 (180–240 ms). The lower arrow indicated the negative peak; the upper arrow indicated the positive peak.

The difference between Figure 2-12a and Figure 2-12b was that all the four components in our hypothesis came into effect on Oz in Figure 2-12a, but not so articulate about P1 and N2 on Fz in Figure 2-12b.

P2 component

Amplitude of P2

As a result of three-way repeated measure ANOVA as Rounds × Colors × Electrode positions, we found Rounds were no significant. Then we put the data from experiment I and II as a mean to analysis two-way repeated measure ANOVA.

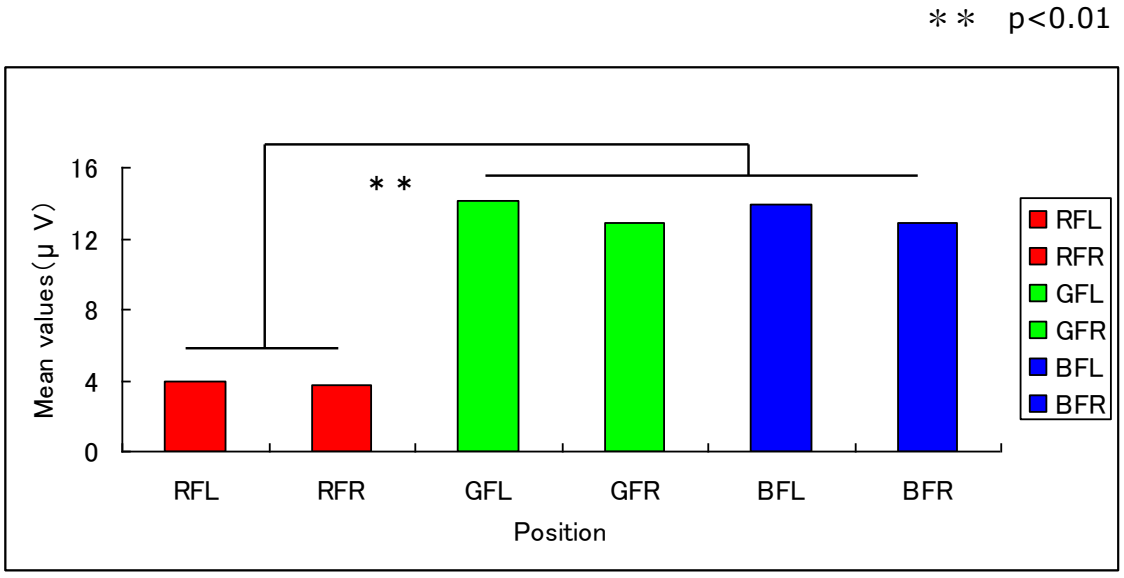


Figure 2-13. The mean amplitude values of P2 on brain frontal positions.

Figure 2-13 shows the mean amplitude values of P2 from subject eight. It shows that RFL(on the left frontal position with red stimuli) and RFR (on the right frontal position with red stimuli) had a significant difference with GFL, GFR, BFL and BFR. But no significantly difference was found on the Middle way (FM).

Latency of P2

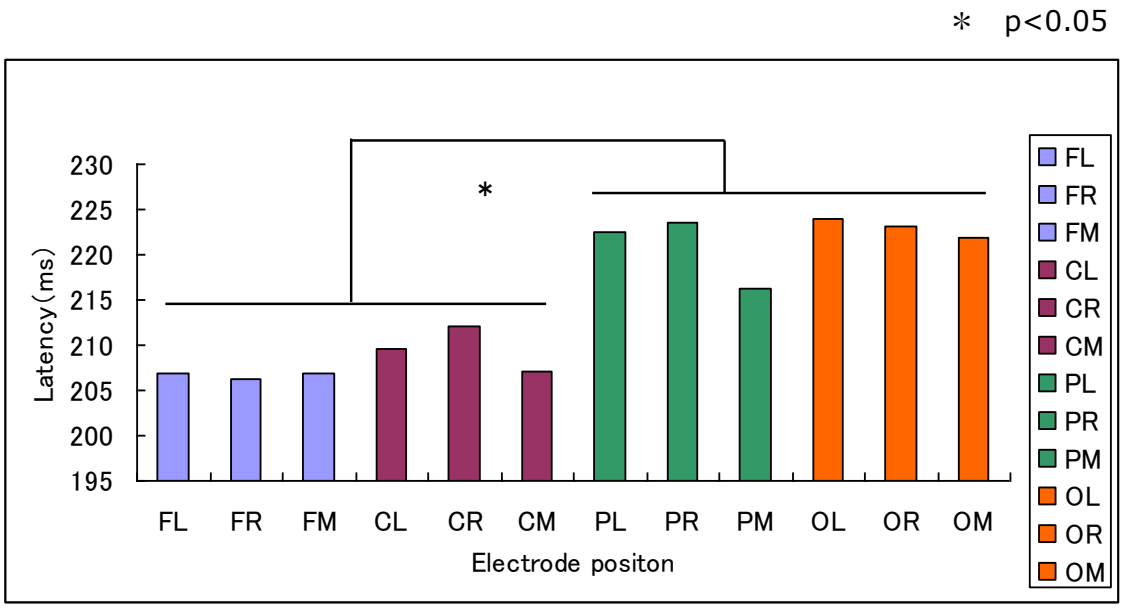


Figure 2-14. The latency of P2 on twelve positions of the scalp.

Figure 2-14 shows that the latency values of P2 from subject eight. It shows that Occipital transmission speed was slower than frontal. But no significant between F and C; P and O.

N1 component

Amplitude of N1

There was no significant on Amplitude by color and position effect.

Latency of N1

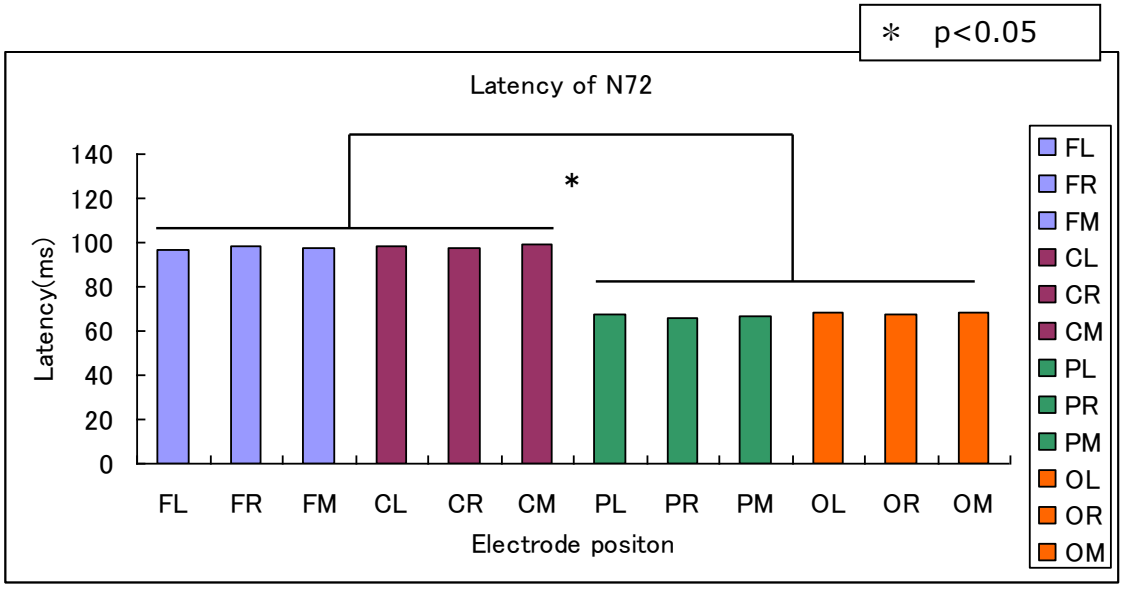


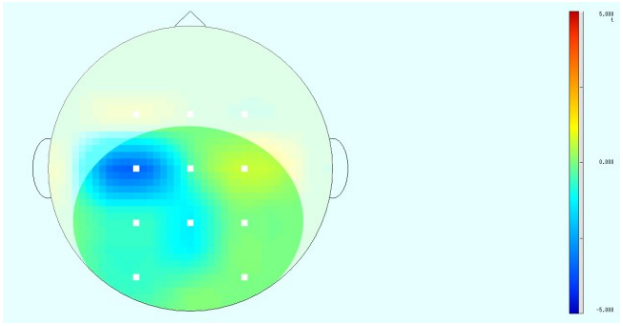
Figure 2-15. The latency of N1 on twelve positions of the scalp.

Figure 2-15 shows the latency values of N1 from subject eight. It shows that Occipital transmission speed was faster than frontal. But no significant between F and C; P and O.

P1 component

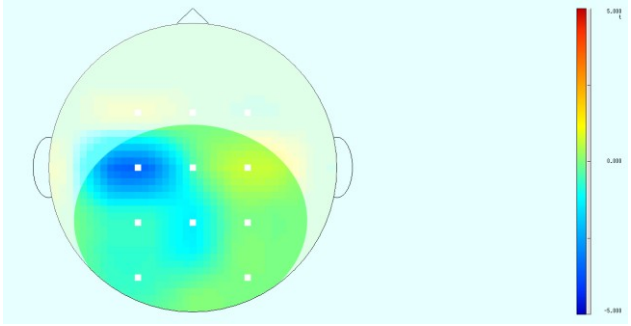
RED-GREEN

In red-green pair, t values show a significant at C3.



RED-BLUE

In red-blue pair, t values show no significant at any position.



GREEN-BLUE

In green-blue pair, t values show significant inclination at O1 and O2.

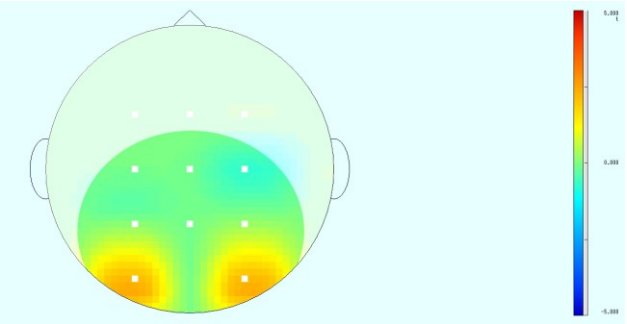
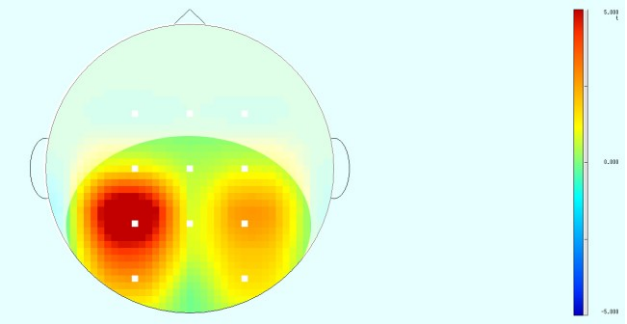


Figure 2-16. The mapping of P1.

N2 component

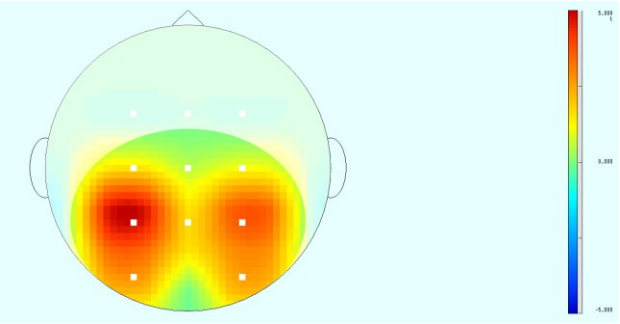
RED-GREEN

In red-green pair, t values show significant at P3 and P4.



RED-BLUE

In red-blue pair, t values also show significant at P3 and P4. And significant inclination at O1 and O2.



GREEN-BLUE

In green-blue pair, t values show a significant at O2.

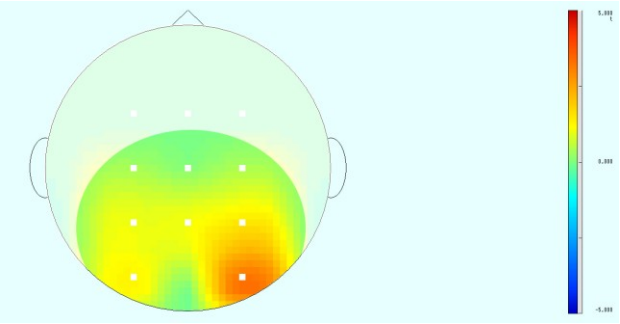


Figure 2-17. The mapping of N2.

2.4. Discussion

2.4.1. VEP repeatability

Our results indicate that although individual difference existed, VEP repeatability has a high success rate. A VEP peak values were obtainable from manual amplitudes and latencies.

The success rate for flash chromatic transient VEP data is likely to be seen that flash chromatic transient VEP is a good way for assessment of color effect in brain cortex activity.

The problem is as discussed earlier, the steady-state VEP consists of consecutive peaks and troughs sinusoidal in morphology so there is no need to choose a component for the peak measurement. However, the transient chromatic VEP may contain several N–P peaks, some of which may represent early or late components or shoulders formed. Ambiguities in the choice of peak component result in exclusion of data. It is also possible that even if an unambiguous N–P-complex can be identified, the peak amplitude of the VEP may be adversely affected by the summation of the responses from the chromatic visual system with the background EEG.

Summation of this kind may result in transient VEPs in which the N- or P-peak, or both, are lowered or raised excessively, resulting in a misleadingly low or high amplitude. The shifting of peak amplitude in this study may not be sufficient to affect VEP results, thereby satisfying the criteria for inclusion in this study. Any shift in peak amplitude may also cause increased scatter of the data and result in poor correlation between VEP amplitude and chromatic contrast. Adding the numbers of subjects maybe a good way for suppressing the scatter of the data.

The success rate for VEP could be raised by greater selectivity of the parameters (window functions and spectral peaks) used to determine VEP amplitude and could be raised also by using relative values against a basic stimuli which likes green-yellow presented with the other spectral stimuli.

2.4.2. The meaning of each component

In previous studies, it can be attributed that there was the first differences appear in time regions preceding the early component peak, when excitation via LGN or post LGN cortical layers to the visual cortex.

When the first color processing starts at LGN cortical layers, the subsequent color

related differences represent later stages of cortical processing occurring in area V4 of visual cortex, possibly involving higher processes simultaneously.It is most likely that, at the early time, activity is produced by cortical mechanisms in visual cortex. And then through any pathway transmit the color information to other cortex for processing.

A glance at Figure 2-12b, Figure 2-13 shows that, for red stimuli later component P200, the positive cortical activity is low on the frontal lobe, whereas for other color stimuli, positive cortical activity seems vitality.

Another one which the interesting things is all the latencies of later component P200 have a significant shorter in frontal lobe to occipital lobe (see Figure 2-14). And the latencies of earlier component N1 have a significant shorter in occipital lobe to frontal lobe (see Figure 2-15). This can be attributed to the generation source of the earlier component N1 means the color information in visual cortex in occipital lobe. But the generation source of the later component P2 is attributed being closed to frontal lobe than occipital lobe. So the color information generated in retina from different types of photoreceptors, and after a relay at the lateral geniculate nucleus (LGN), color information is transmitted to the cerebral cortex. The outputs of color-opponent cells are linearly combined in the primary visual cortex (Vl) to form neurons tuned to various directions in color space at the third stage. Nonlinear interactions of the signals from these neurons occur at the fourth stage, which involves Vl and V2, and cells tuned to a narrow range of hue or saturation are formed. The effect of illumination is discounted at the fifth stage, which involves V4, to form neurons whose responses parallel the perceived surface color as a result of color constancy. Different color processing stages in the cortex are indicated by different shadings.

After V4, there must be several inferior cortexes continue on information processed. In our study, as the analysis on the components P1 and N2, we have seen an inclination that the information about chromatic lights may be send passing a cortex called inferior temporal cortex (see Figure 2-17). We have known that there existed a pathway for chromatic information passed inferior temporal cortex in the animal experiments. The findings of the present study are in agreement with the result from animals experiments. It was considered that visual cortex generated the color, and then transmitted passing inferior temporal cortex to the frontal lobe, the color perception was processed in frontal lobe, and relay back to the cerebral cortex for sending orders.

The difference on amplitude of P2 which was found between the frontal and occipital lobe also indicated a possibility about the light intensity. It means the light intensity will be an important factor to the experiment about the chromatic lighting.

2.5. Conclusions

In the present experiment, we examined the repeatability of VEPs. The results which indicated the VEPs with a good repeatability show a high possibility to use VEP to evaluate activity of the cerebral cortex. The application of VEP is not only confined to a normal neurological clinical examination of vision until the visual cortex, but also extended to the information pathway after visual cortex.

A number of approaches have been used in attempts to isolate magnocellular/ parvocellular activity in psychophysical and non-invasive electrophysiological tests. In a series of reports, scientists have documented visual evoked potentials (VEPs) will be a good choice. As the different kind of stimuli, we can comment on the use of VEPs response to assess activity in the magnocellular and parvocellular system to check the dorsal and ventral visual pathways in object or color processing.

The present study surveys the processing after visual cortex with the chromatic lights. And evidence that VEPs will be a good simple method for estimating the brain cortex's physiological responses by using a non-invasive electrophysiological tests.

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Chapter 3

The effects of monochromatic light on different time intervals

3.1. Background

Time is an essential guiding force of behavior for everyday activities, from our sleep-wake cycle to walking, speaking, playing and playing sports. Human beings are continually engaged in these activities because, like most animals, we process and use temporal information across a wide range of intervals. Several measures of information processing of the stimulus have been studied in relation to time perception, such as interest, processing times, originality, complexity, and attention. And so many factors could affect the time perception,

Although an increasing number of studies have investigated the role of color effects in cognitive activity, only a limited number of studies have analyzed the relationship between ambient color light and estimation of time durations. Furthermore, these studies have typically yielded inconclusive results regarding the precise nature of the relation.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; Hanifin 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 time scales 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.

In this chapter, we tested the hypothesis that ambient color light induced by different wavelength light systematically influence error in time perception. In particular, our hypothesis was that the perceived duration of time estimation is affected by manipulation of brain arousal level. We used monochromatic color stimulus material standardized for the lighting intensity in order to effectively manipulate the color effects. 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.

3.2. Methods

3.2.1. 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.

3.2.2. Measurements

3.2.2.1. General procedures

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 3-3. There were four conditions (Red, Green, Blue I and Blue II). The spectral distribution curve and color diagram of each light conditions are showen in Figure 3-1 and Figure 3-2. All the experiments were conducted during the same 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.

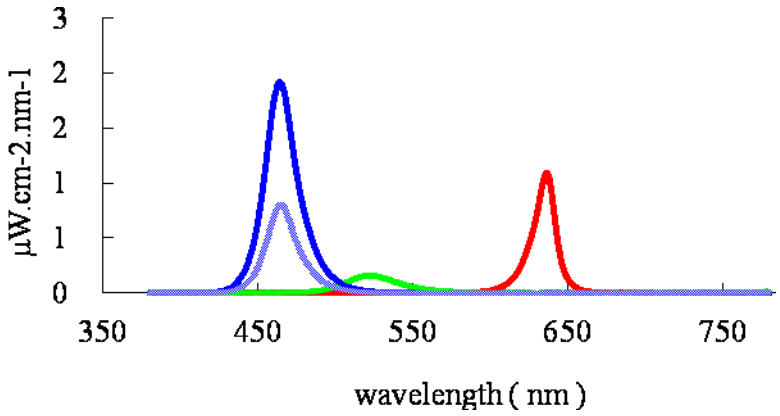

Figure 3-1. Spectral distribution curves of the red (—) , green (—) , blue I (—) and blue II (··) light conditions.

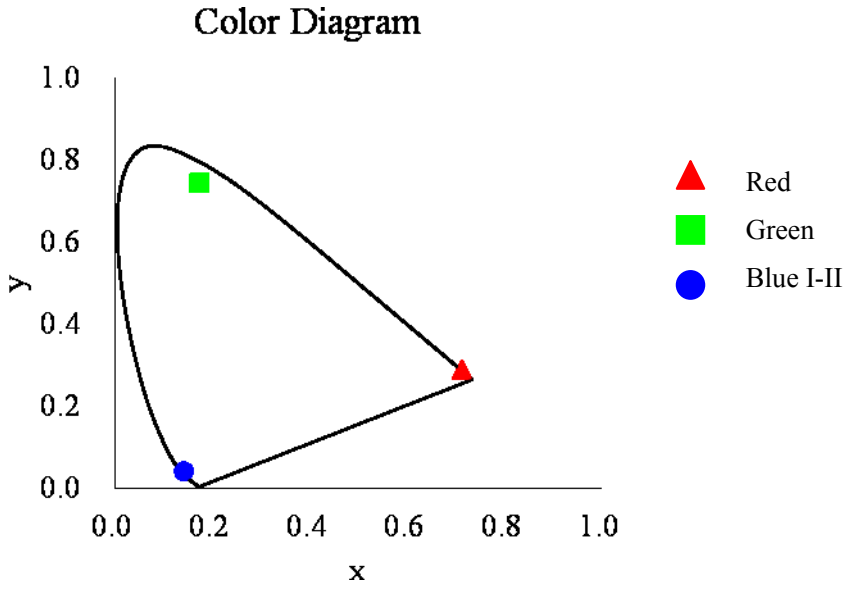

Figure 3-2. Color Diagram of the red, green and blue I-II light conditions.

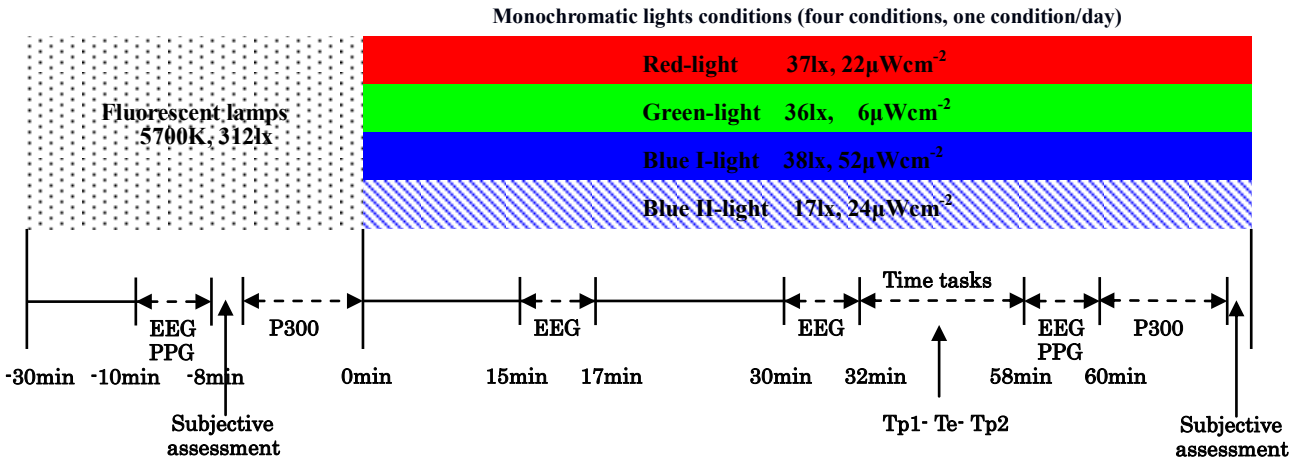

Figure 3-3. The experimental protocol. After one hour light exposure, the subjects were asked to perform three sessions of intermittent isometric MVCs. The EEG and the EMG single were recorded during the experiment. The subjective assessments were asked in initial and final stage of the experiment.

3.2.2.2. Time task

As shown in Figure 3-3, 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.

3.2.3. 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 37 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.

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 to analyze the color effects. The brightness of each light condition, which was only asked after light exposure, we used a one-way repeated-measure ANOVA in the red, green and blue I group and a paired t-test in the red, blue II group and 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.

3.3. Results

3.3.1. Behavioral performance data

Figures 3-4 and 3-5 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 3-6).

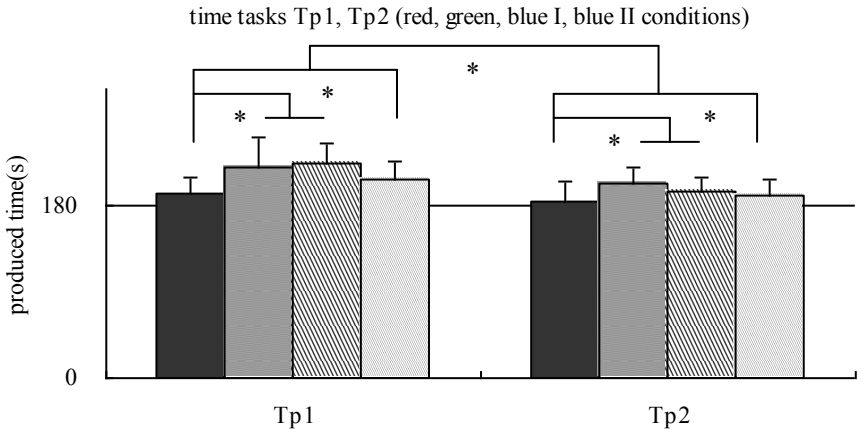

Fig. 3-4. Mean values of the two 180-s time production tasks in the red (■), green (■), blue I (■) and blue II (■) light conditions (* $p<0.05$).

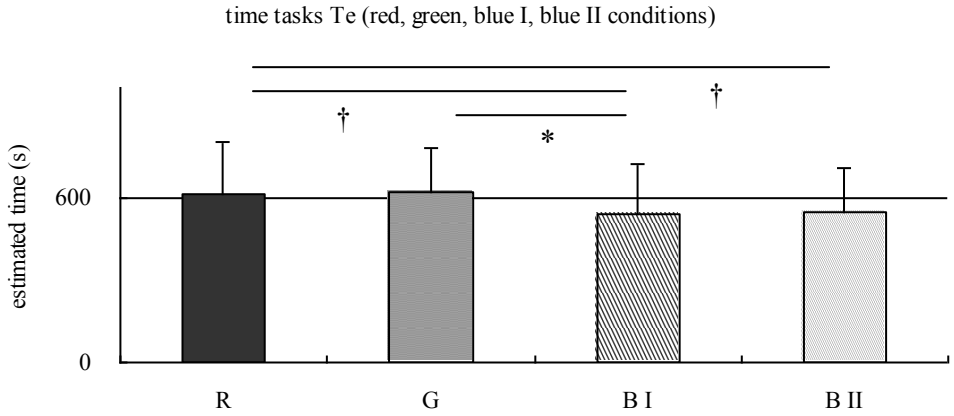

Fig. 3-5. Mean values of the 600-s time tasks in the red (■), green (■), blue I (■) and blue II (■) light conditions (* $p<0.05$; † $p<0.1$).

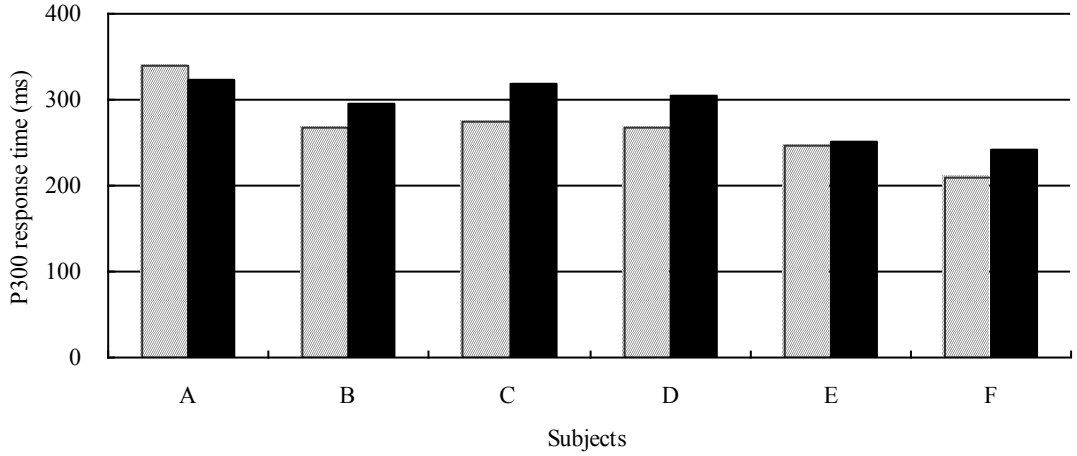

Fig. 3-6. Mean values of P300 response times for six subjects in the red (■) and blue II (■) light conditions. The difference of P300 response times between the two conditions showed a significant trend (p=0.067).

3.3.2. 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 3-7. 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 3-8). 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 3-9). 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). 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) (Figure 3-10). However, no significant difference was found among the color light conditions.

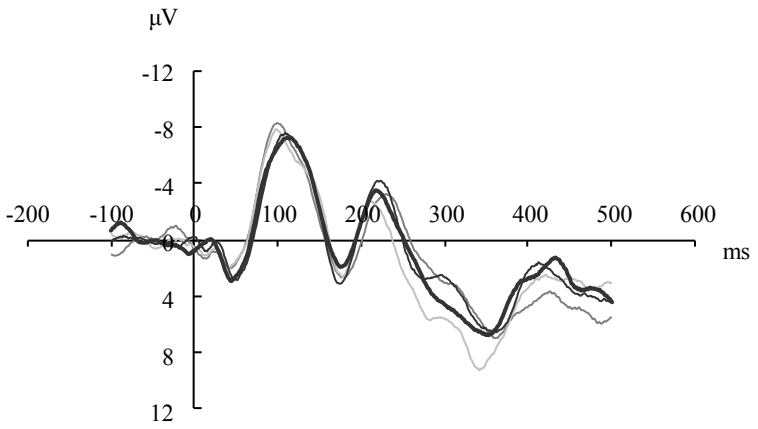

Fig. 3-7. The grand averaged P300s obtained at C4 after one hour of light exposure in the red （—）, green （—）, blue I (—) and blue II (—) light conditions.

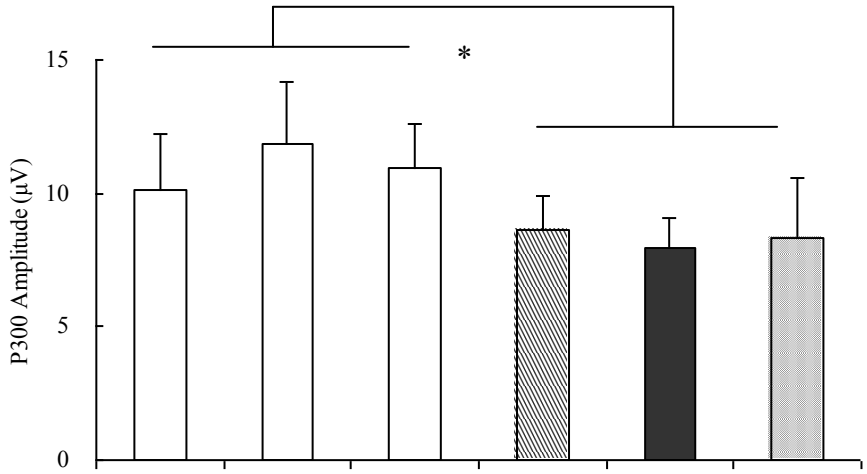

Fig. 3-8. Mean values of P300 amplitudes at Cz in the baseline conditions (□), in the red (■), green (■) and blue I (■) light conditions. The amplitudes became significantly smaller after the monochromatic light exposure than the baseline conditions (p=0.016)

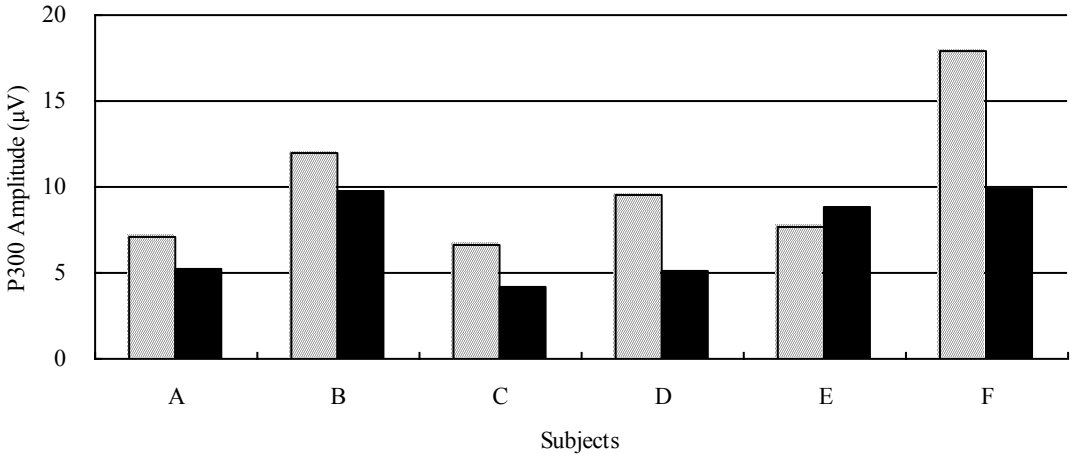

Fig. 3-9. Mean values of P300 amplitudes for six subjects at C4 in the red (■) and blue II (■) light conditions. The difference of P300 response times between the two conditions showed a significant trend (p=0.063).

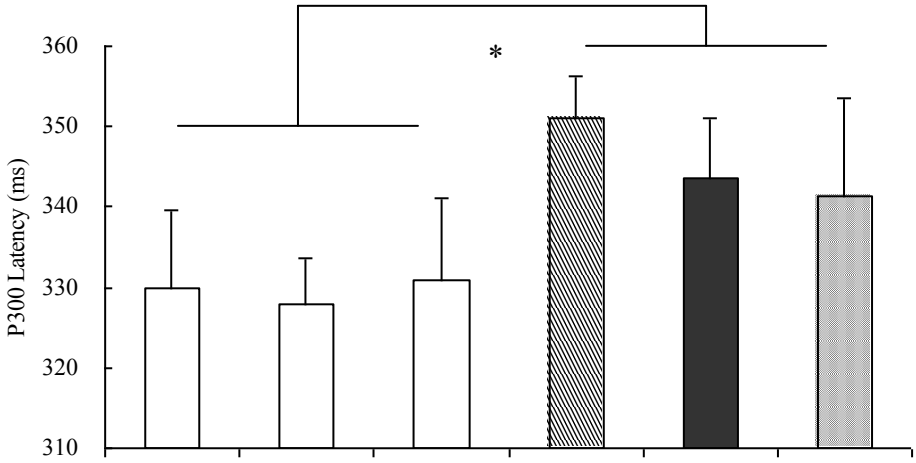

Fig. 3-10. Mean values of P300 latencies at Cz in the baseline conditions (□), in the red (■), green (■) and blue I (■) light conditions. The latencies became significantly longer after the monochromatic light exposure than the baseline conditions (p=0.047).

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 3-11). 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 3-12).

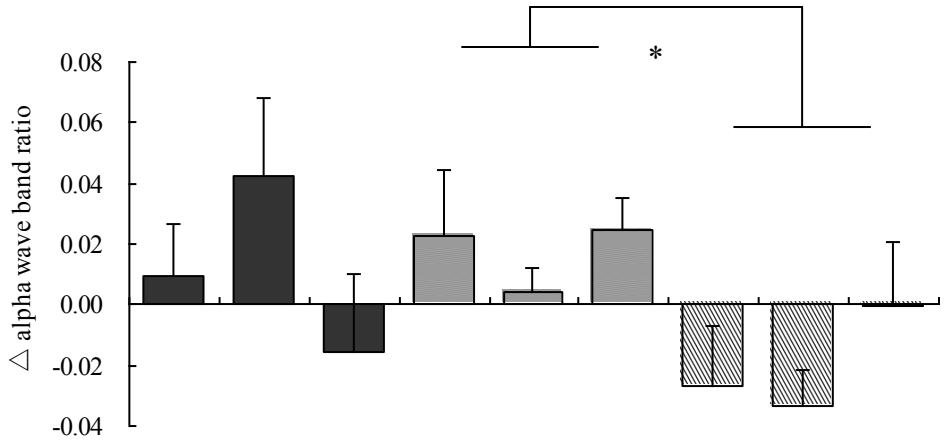

Fig. 3-11. The power spectrum of EEG alpha wave changed to the baseline conditions at C3 in the red (■), green (■) and blue I (■) light conditions in different time zones. The left column showed the EEG data measured after light exposure for 15~17 min; the middle column showed the EEG data measured after light exposure for 30~32 min; the right column showed the EEG data measured after light exposure for 58~60 min (p=0.047).

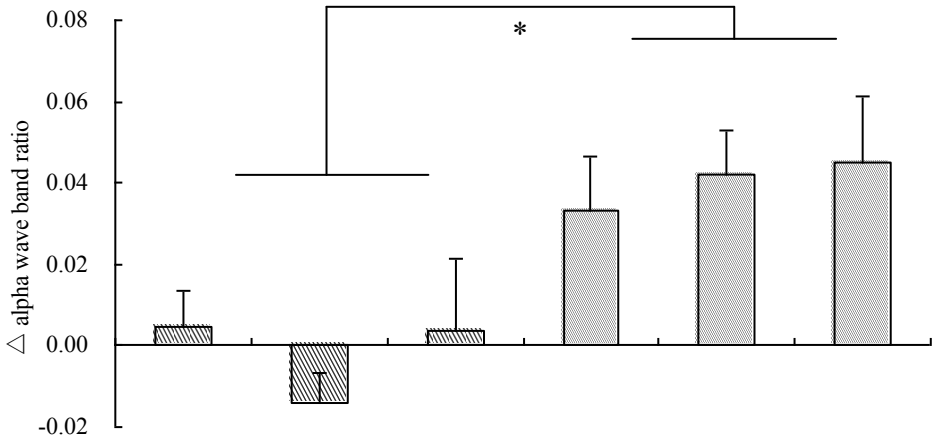

Fig. 3-12. The power spectrum of EEG alpha wave changed to the baseline conditions at Cz in the blue I (■) and blue II (■) conditions in different time zones. The left column shows the EEG data measured after light exposure for 15~17 min; the middle column shows the EEG data measured after light exposure for 30~32 min; the right column shows the EEG data measured after light exposure for 58~60 min in each conditions (p=0.024).

SDPTG:

As shown in Figure 3-13, 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 and 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).

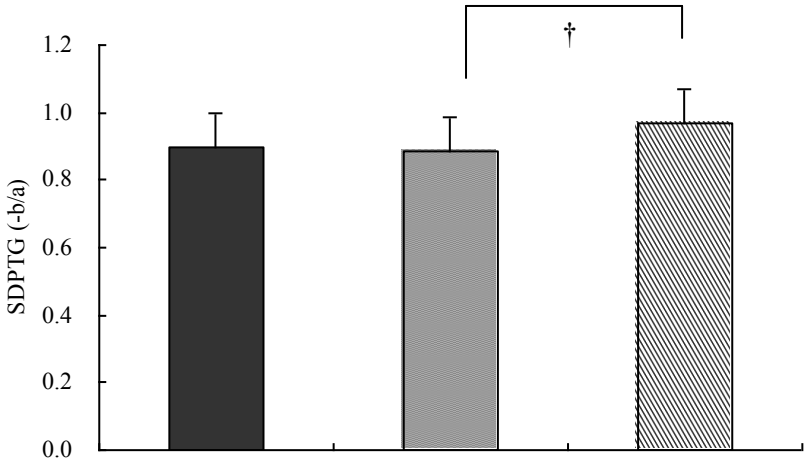

Fig. 3-13. The SDPTG values measured between 58~60 min after light exposure in the blue I (■) light condition tended to be significantly faster than those after exposure in the green (■) light condition (p=0.057).

3.3.3. Subjective assessments data:

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 3-14). 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.

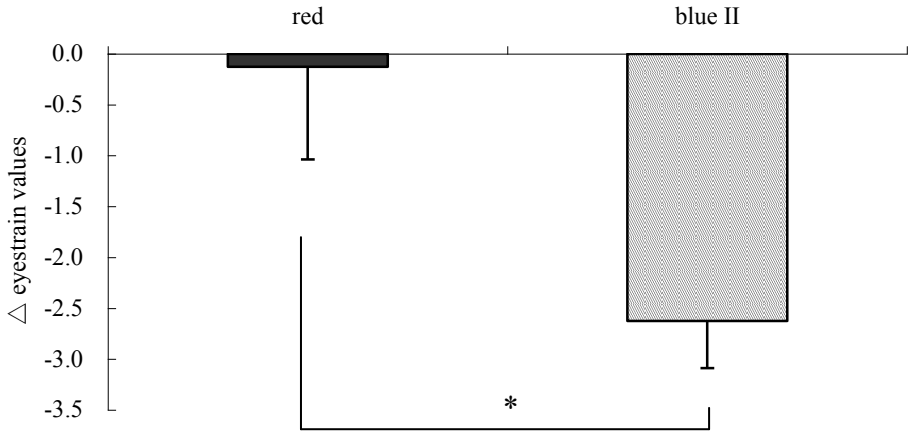

Fig. 3-14. The subjective assessment values of eyestrain changed to the baseline conditions in the red (■) and blue II (■) light conditions. The larger values mean the lower eyestrain level. The relative values were significantly larger in the red light than in the blue II light condition (p=0.049).

3.4. 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 3-5), and the amplitudes of the blue II light condition tend to be significantly larger than those of the red light condition (Figure 3-7) 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 there may be 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 3-8), and the relative values were significantly decreased in the blue I light condition compared to the blue II light condition (Figure 3-9). 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.

3.5. 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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Chapter 4

The effects of monochromatic light on muscle strength

4.1. Background

Monochromatic light is light consisting of a single pure frequency. The visible light spectrum shows all the possible colors that can be made out of monochromatic light. Researching of monochromatic light helps us to understand the effects of ambient light illumination, and color plays a major role in this process. Color vision is an essential part of everyday life, and it plays a crucial role by acting on other sensory, motor and information processing systems (Shams et al., 2002). Colored light may shift circadian rhythms (Morita and Tokura, 1998), which can lead to change in body temperature and melatonin secretion (Hoffmann et al., 2008). Color-evoked changes in taste (Katsuura et al., 2005), mood (Hoffmann et al., 2008), cognition (Bedwell and Orem, 2008), time perception (Huang et al., 2012), motor cortex excitability (Langguth et al., 2009) and muscular strength (Crane et al., 2008) have been reported. Some psychological studies focus on the color image effect. For example, Pellegrini et al. (1981) tested the aggression in a criminal detention to investigate the 'Tranquilizing Pink' with a room color Room Color.

Recent studies aimed to find a correlation between environmental lighting and human performance and health, with positive results where insufficient or inappropriate light exposure can disrupt standard human rhythms which may result in adverse consequences for performance, safety, health (Daurat et al., 1993; Knez and Kers, 2000; Partonen and Lönnqvist, 2000). The direction is pointed out by the recent discoveries in photobiology that are creating a link between lighting and health and well-being. In humans it has been reported recently that even small changes in ordinary light exposure (~100 lx) can significantly affect both plasma melatonin concentrations and the entrained phase of the human circadian pacemaker (Zeitzer et al., 2000). The study which used 9.9~12.1μWcm^{-2} light source indicated the frequency-specific changes in the waking EEG showed the 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 and increase the brain arousal level (Lockley et al., 2006).

Muscle strength is a complex and multifaceted process involving physiological, biomechanical and psychological factors, and many researchers have investigated the effects of color on muscular strength (Green et al., 1982; Profusek and Rainey, 1987; Schauss et al., 1979, 1981; Smith et al., 1986; Elliot and Maier, 2007; Crane et al., 2008; Elliot and Aarts, 2011), though the results were inconsistent. Green et al. (1982) found that grip strength was higher after subjects viewed red than either blue or pink

when these hues were projected onto a wall for 30 sec. Regarding the role of ambient colored light on muscular power and strength, Crane et al. (2008) reported that average muscular power was significantly higher under red light compared to blue light or white light, and grip strength was significantly higher in a room with white light as compared to that in a room with blue light. However, others showed that muscular strength had no significant association with color. For example, Profusek and Rainey (1987) showed that subjects experienced a significantly lower level of anxiety in a pink room, but no significant difference was found on grip strength or motor precision. Schauss et al. (1979, 1981) reported that the use of a specific shade of pink can have a moderating effect on subjects experiencing feelings of anger or agitation. Smith et al. (1986) suggested that there was a sex difference with regard to demand characteristics for different colors. Elliot and Maier (2007) proposed that red may be associated with threat and danger. Such variability in results may be related to variable methods or perhaps deficiency in study design or analysis of the results. Only Elliot and Aarts (2011) emphasized the importance of rigorous experimental methods when testing color effects, when they suggested that the participants who viewed red while engaging in a pinchgrip or handgrip task produced greater strength output and facilitated the velocity of that force. The color of the environment may affect performance (Kwallek et al., 1998; Kwallek and Lewis, 1990) and perceptions of the task (Stone and English, 1998), depending on the demands of the task.

These previous studies had several problems: 1) most of the studies were psychological studies using self-report measures (for example, Viola et al., 2008; Russell and Robert, 2005); 2) the studies did not have a standardized method for reporting stimuli colors; 3) several studies used reflected lighting as stimuli colors (for example, Dunwoody, 1993); 4) the studies featured different inter-trial resting periods (for example, Profusek and Rainey, 1987; Dunwoody et al., 1996).

In consideration of inconsistent light conditions, we need to enrich the data about monochromatic lights based on rigorous experimental methods. Therefore, in the present study, we designed a method to examine the effects of monochromatic lights of different light intensity standardized as illuminance and irradiance to investigate whether the light power affect to the muscle performance and we chose the index finger to investigate the muscle strength performance during muscle measurement task. Finally, we also attempted to find a connection between muscle performances and brain activity.

4.2. Methods

4.2.1. Subjects

Six healthy young adult male volunteers, age 25-27 years, participated in the present study. They were sufficiently informed about the experimental procedure and gave written informed consent for study participation. To avoid muscle fatigue that could lead to biased torques, participants were instructed to refrain from participating in any rigorous physical activity or consuming alcoholic drinks or caffeine-containing food during the 24 h preceding the experimental session.

4.2.2. Measurements

4.2.2.1. General procedures

Twenty-five monochromatic light-emitting diode (LED) lights were set in front of subjects. To ensure even illumination, we put a filter between the light source and the subjects. We standardized measurement units to verify the different unit effects in the following classification: illuminance (red, green and blue I) and irradiance (red and blue II). The spectral distribution curves are shown in Figure 4-1. The color diagram is shown in Figure 4-2. The illuminance and irradiance of the four light conditions are shown in Table 4-1. Before the experiment, fluorescent lamps (5700 K) in a climatic chamber (25 ℃, 50% relative humidity) were turned on to stabilize the illuminance (312 lx).

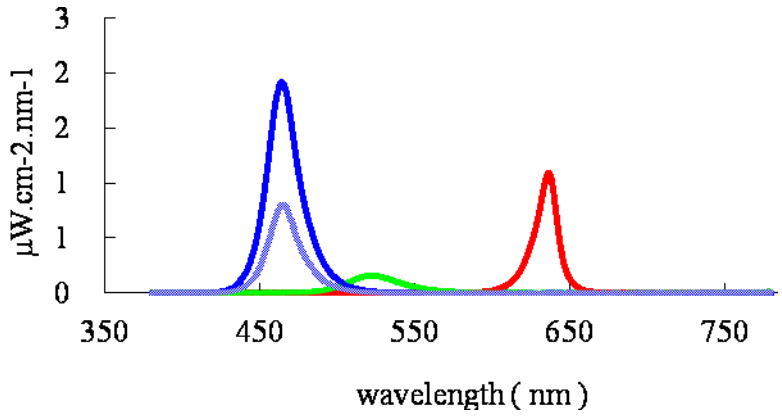

Figure 4-1. Spectral distribution curves of the red (—), green (—), blue I (—) and blue II (‥) light conditions.

Table 4-1. Illuminance and irradiance of red light, green light, blue I light and blue II light conditions.

Illuminance (photopic-lx)		Irradiance (μWcm^{-2})
red light	37	22
green light	36	6
blue I light	38	52
blue II light	17	24

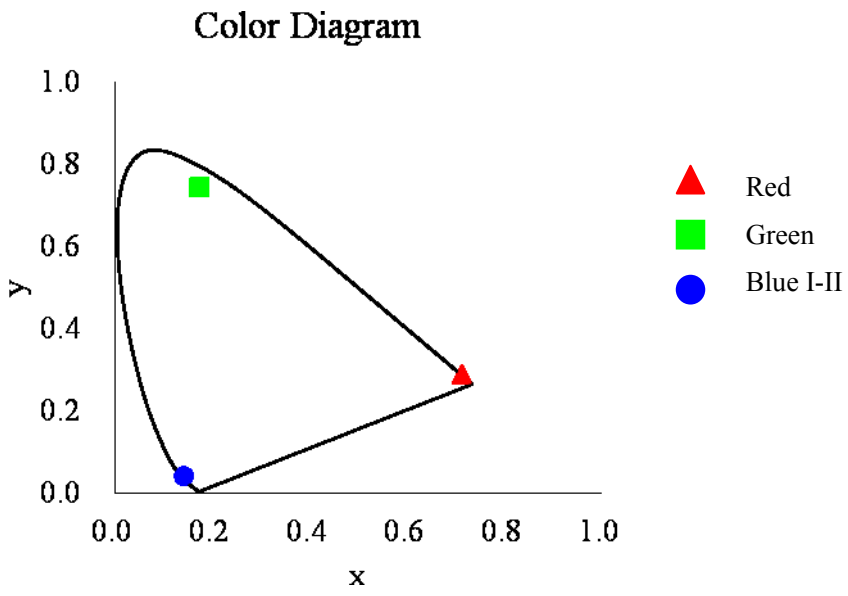

Figure 4-2. Color Diagram of the red, green and blue I-II light conditions.

In the experiment, each subject entered the climatic chamber and sat on a comfortable chair quietly for 30 min to get accustomed to the surroundings. During the 30 min we attached EEG and EMG electrodes. Subsequently, we adjusted the subject's position and fixed the right arm on the experimental setup as shown in Figure 4-4. Next, the fluorescent lamps were turned off, and then the monochromatic lights were turned on and stayed on until the experiment ended. After one hour of light exposure, each subject performed a muscle measurement task. During the experiment, we examined each subject's EEG, P300 and EMG results. The experimental protocol is shown in Figure 4-3. The four light conditions (red, green, blue I and blue II) of the experiment were conducted during the same hours (13:00-15:00) but on separate days. To consider the influence of the experiment day compared to the next day, the interval between each two sets of conditions was at least 3 days. The order of color conditions was counterbalanced among the subjects.

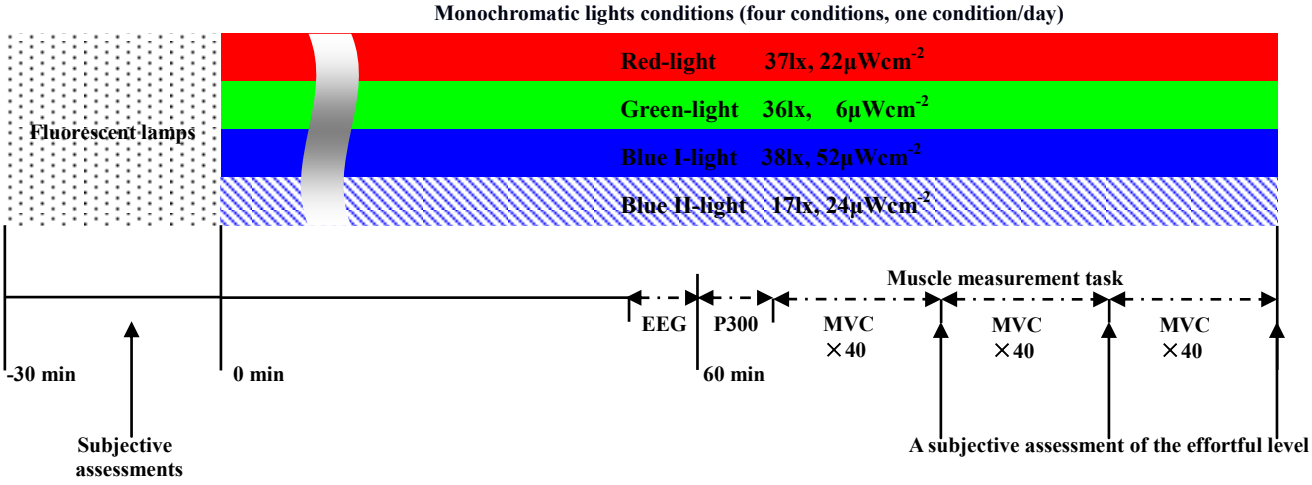

Figure 4-3. The experimental protocol. After one hour light exposure, the subjects were asked to perform three sessions of intermittent isometric MVCs. The EEG and the EMG single were recorded during the experiment. The subjective assessments were asked in initial and final stage of the experiment.

4.2.2.2. Muscle measurement task

After 60 minutes of light exposure, each subject performed three self-regulated sessions of intermittent isometric maximal voluntary contraction (MVC). Each session contained forty trials of MVC. The interval between each set of two trials was confined to less than 30 seconds, and all the subjects were asked to memorize the chosen selective interval that they performed at the beginning and repeat it in the subsequent experiment sessions as consistently as they could. At the end of each session, the subject was asked to completely relax the index finger for 1 min, and during the rest time, the subject was asked to provide a subjective assessment, using his left hand, of the effort level of the right hand, to make sure the subject had made the best effort during each period.

4.2.2.3. Recordings

The right hand was positioned in an apparatus where the wrist and fingers, except the index finger, were constrained (Figure 4-4). The index finger was free to move in the horizontal plane. A piezoelectric force transducer (TECA SA-30A) was in contact with the first phalanx of the index finger.

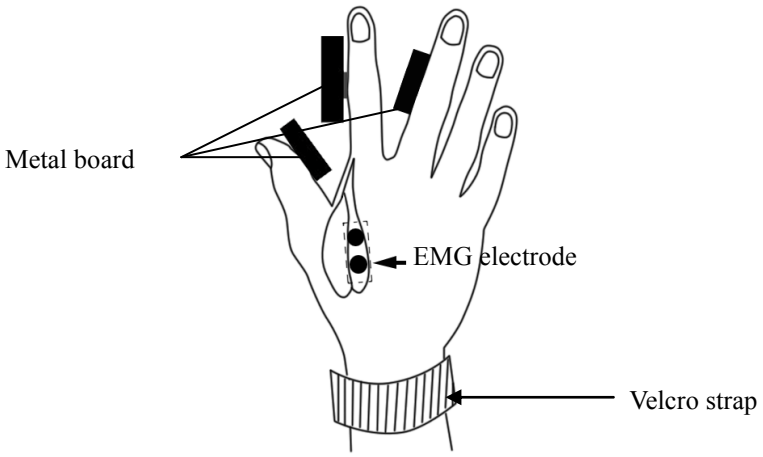

Figure 4-4. Schematic drawing of the experimental set-up. The right hand is constrained at the wrist level. The index finger is placed in an anatomical support and a piezoelectric transducer measured force. Forward hand shift is avoided with a constraint at the thumb. The index support and all constrains are adjustable in position to adapt to the anatomy of the subject.

The surface EMG signals were recorded from the first dorsal interosseous (FDI) muscle abduction in the right hand. A bipolar electrode (Biopac, Inc., USA, TSD150B, Ag/AgCl, diameter 11 mm, inter-electrode distance 20 mm and a bandpass of 12 to 500 Hz) was positioned on the muscles, which were identified by palpating the skin when subjects flexed and extended the fingers after skin abrasion and cleaning the skin with alcohol. A reference electrode was placed on the skin overlying the back of the left wrist. One second of EMG recordings was obtained before and after muscle measurement task as shown in Figure 4-7. The electrode was taped onto the skin firmly to reduce movement artifacts and remained in place throughout the study.

To determine the cortical correlate of the muscle activities, we recorded electric potentials at the Fz, C3, Cz and C4 recording sites based on the International 10/20 system (Nihon Kohden, Inc., Japan, NE-113A, Ag/AgCl, diameter 9 mm and a bandpass of 0.032~60 Hz). The reference electrodes (A1 and A2) were on the earlobes.

The ground electrode was on the forehead. An electrooculogram (EOG) (the same bandpass as that for the EEG) was recorded to exclude segments with eye movement artifacts. To evaluate the cognitive function, we elicited the P300 component of the event-related brain potential by an auditory "oddball" paradigm (1000-Hz standard sound-80% and 2000-Hz target sound-20%, 65 dB SPL auditory stimuli by an earphone).

All the data were recorded at a sampling rate of 1000 Hz on a laptop computer by a data acquisition system (Acqknowledge 3.9.1, Biopac Systems, Inc.).

4.2.3. Data analysis

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

The red light, green light and blue I light conditions were classified as illuminance, which was approximately 37 lx; the red light and blue II light conditions were classified in irradiance, which was approximately 23 μWcm^{-2}. The blue I light and blue II light conditions 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 interval in muscle measurement task:

The subjective time interval between trials assessed the willing of explosive muscle strength in sessions 1, 2 and 3 during a strong muscle contraction in muscle measurement task. The mean values were calculated for every session of forty contractions trials. We used a two-way repeated-measure ANOVA (color × order) in the three color groups.

%MVE:

The MVE values were defined to assess the maximal forceful exertion of muscle performance in the muscle measurement task. The %MVE values for the FDI muscle were calculated for a normalization procedure. In this processing, the raw data were first processed into the root mean square (RMS). Two hundred samples RMS-converted signals were plotted. Afterwards the EMG signals collected during FDI muscle abduction were expressed as percentages of the calculated mean RMS of MVE (%MVE). We used a two-way repeated-measure ANOVA (color × order) in the three color groups on the mean values of %MVE in every session of muscle measurement task.

EEG:

We calculated the alpha wave band power ratio (alpha / (alpha+beta) ratio, alpha band as 8~13 Hz and beta band as 13~30 Hz). A one-way repeated-measure ANOVA was used in the red, green and blue I groups at Fz, C3, Cz and C4. A paired t test was used in the red, blue II group and blue I, blue II groups at Fz, C3, Cz and C4.

P300:

A one-way repeated-measure ANOVA was conducted on the amplitude and the latency of P300 in red, green and blue I group at Fz, C3, Cz and C4. A paired t test was used in the red, blue II group and blue I, blue II groups at Fz, C3, Cz and C4.

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 a statistically significant trend was set at 0.1.

4.3. Results

MVC assessment had been excluded as measure miss of two subjects. Instead of the MVC data, we used the time interval between trials in the muscle measurement task and the MVE data to assess the motor performance.

4.3.1. Behavioral performance data

Time interval in the muscle measurement task: No significant difference was found between the red, green, blue I group and the red, blue II group. However, the color main effect tended to be significantly different in the blue I, blue II group. The time interval during which subjects exerted their muscular power by themselves tended to be faster under the blue I condition than under the blue II condition, as shown in Figure 4-5 (p=0.075).

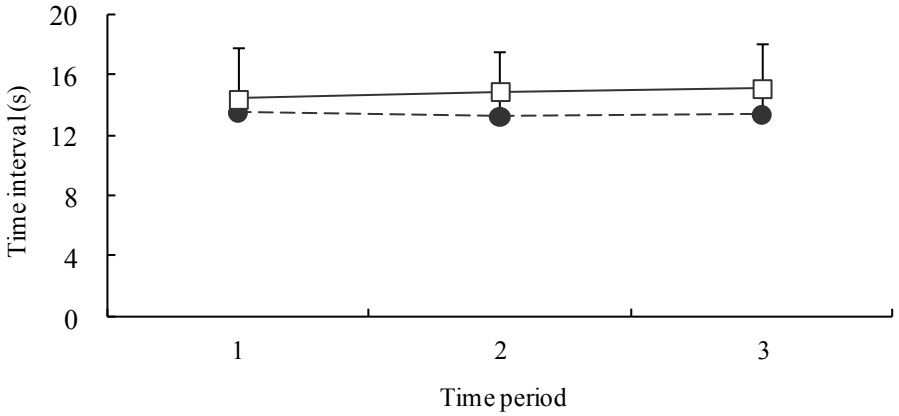

Figure 4-5. Mean time interval of three sessions during the muscle measurement task. Time interval of blue I (●) and blue II (□) light conditions are shown in the graph. Trend differences were observed between two blue light conditions of different intensity (p=0.075).

4.3.2. Electrophysiological data

%MVE:

The order main effect tended to be significantly different in the red, green, blue I group ($p=0.016$) compared to the other groups. The time period 1 was significantly larger than time period 2 ($p=0.032$), and likewise was larger than time period 3 ($p=0.053$). Figure 4-6 shows all six subjects' EMG results during the task performance under the green light condition. No significant difference was found in the red, blue II group or the blue I, blue II group.

Figure 4-7 shows raw EMG data of one subject in the red light condition at the beginning (initial) and the end (final) of muscular isometric maximal voluntary contractions.

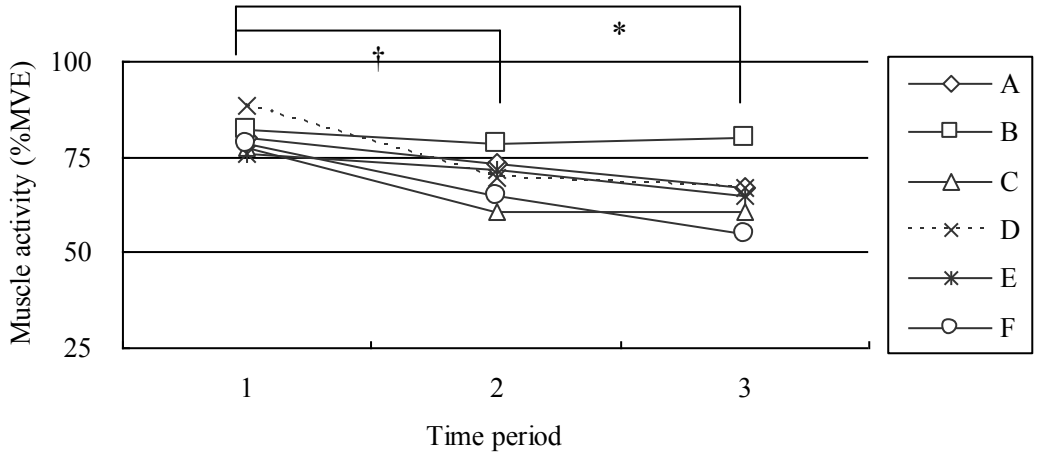

Figure 4-6. Mean voluntary EMG electrical activity of all six subjects during the muscle measurement task (1, 2 and 3) in green light condition. (†, $p<0.1$; *, $p<0.05$)

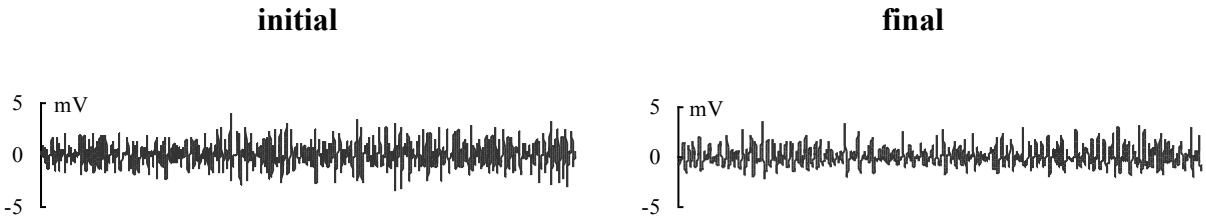

Figure 4-7. Typical sets of computer outputs showing raw EMG data of one subject in the red light condition at the beginning (initial) and the end (final) of muscular isometric maximal voluntary contractions.

EEG:

The one-way repeated-measures ANOVA was used in the r-g-bI groups at Fz, C3, Cz and C4 was no significant difference.

A paired t test was used in the r-bII group showed a trend significance at Fz (p=0.064) and a significant difference at Cz (p=0.042) (Figure 4-9).

A paired t test was used in the r-bII group was no significant difference at Fz, C3, Cz and C4.

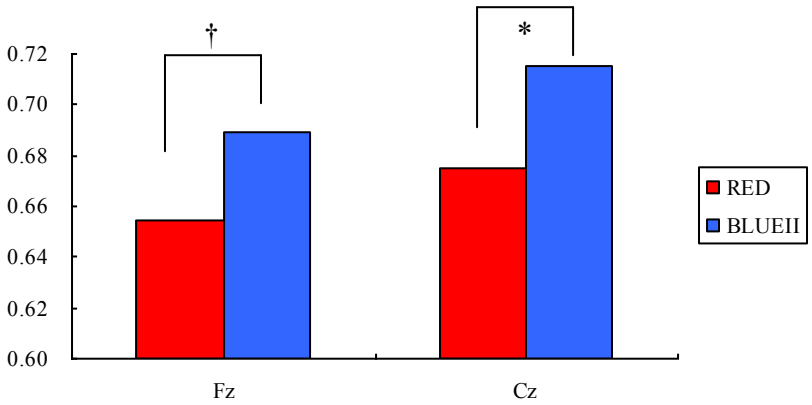

Figure 4-9. The values of alpha wave band power before muscle measurement task. The values trended to be significantly larger in blue II than in red light condition at Fz (†, p=0.064), moreover, a clear significantly different was found in blue II than in red light condition at Cz (*, p=0.042)

P300:

No significant difference was found in latency of P300 in the three color groups. However, the response time of P300 showed a trend significant difference in red and blue II light condition. The values of RT in blue II trended to be significant difference smaller than in red light condition (p=0.067) (Figure 4-8).

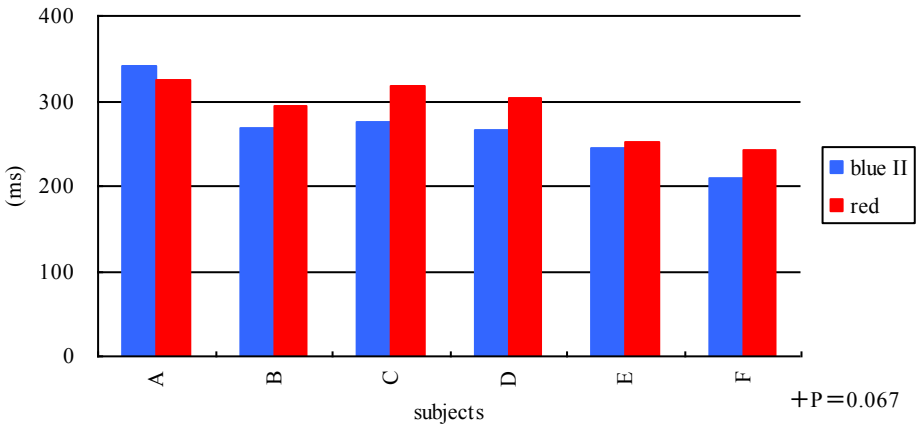

Figure 4-8. The graph showed all six subjects' data in response time of P300 before muscle measurement task. The response time in blue II trended to be faster than in red light condition (p=0.067, †, p<0.1)

The amplitude of P300 at C4 tended to be significantly larger under the blue II condition compared to the red light condition (p=0.063) and to the blue I light condition (p=0.093) (Figure 4-9).

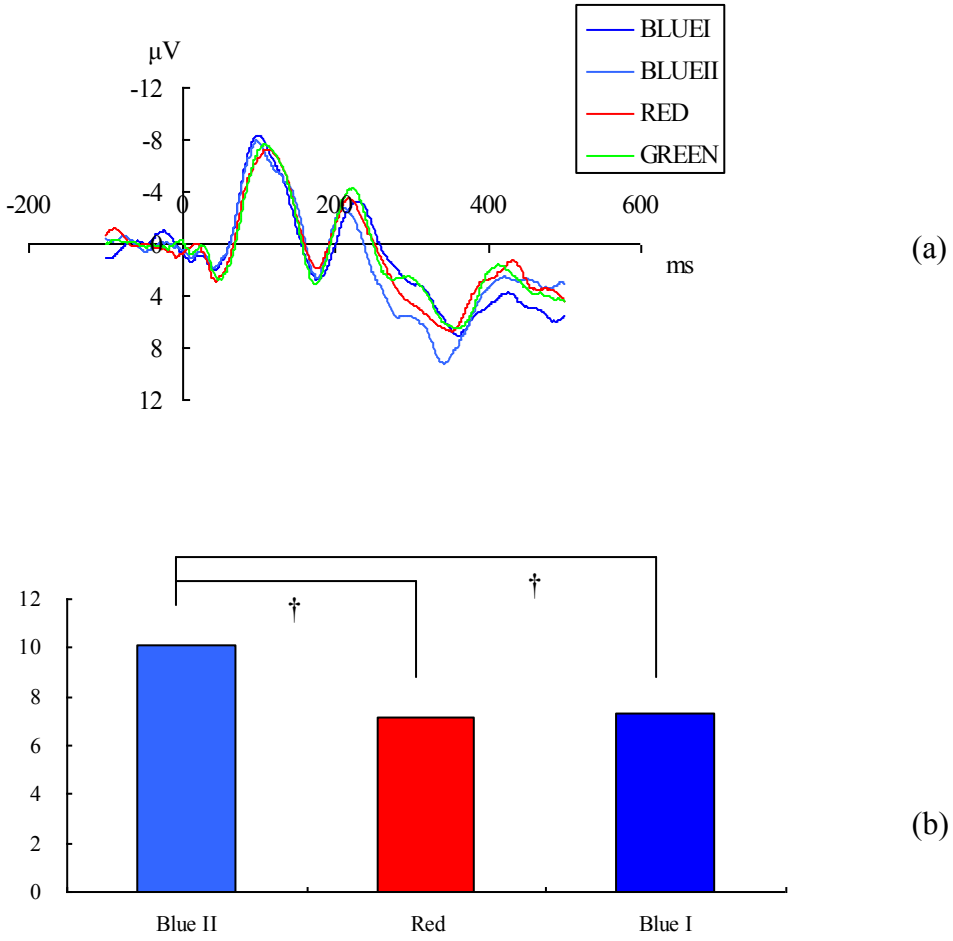

Figure 4-9. (a) The grand averaged P300s at C4 in all four color-light conditions before muscle training. (b) The amplitudes of P300 at C4 tended to be significantly larger in blue II light than in red light condition (p=0.063) and in blue I light condition (p=0.093) (†, p<0.1).

4.4. Discussion

The purpose of the present study was to investigate the effect of monochromatic lights on muscle strength output. Motor performance was assessed during a time interval of explosive muscle strength in a muscle measurement task and %MVE. In the present study, the time interval tended to be faster under the high-intensity light condition (blue I) than under the low-intensity light condition (blue II), which may indicate that the willing of subjective muscle strength output tended to be higher under brighter light conditions (Figure 4-5). In a sense, a similar perspective on brightness of light has been found in some previous studies, one of which indicated that ambient lighting levels can have a substantial impact on performance and that bright ambient illumination may be effective in maintaining optimal levels of alertness during night shift operations (Campbell and Dawson, 1990). And the other one indicated that exposure to bright light in the morning and evening in the workplace improved self-reported mood, energy, alertness and productivity in individuals with "sub-syndromal seasonal affective disorder" (Avery et al., 2001). Although compared to the previous studies, the light condition setting is on a dim level in this study, however, several previous studies (Bovin et al., 1996; Zeitzer et al., 2000) also reported a dim level light exposure could significantly affect both plasma melatonin concentrations and phase advance the human circadian pacemaker.

The MVE values were significantly different among time periods 1, 2 and 3 (Figure 4-6). However, no significant difference was found among the color conditions. These results indicated that after one hour of light exposure, little significant difference in muscle performance was found base on the color effect. Several studies have highlighted the danger or threat effect of red (Payen et al., 2011; Elliot and Aarts, 2011). These studies proposed that the immediate, urgent response to red may be a subcortically based “call to arms” involving fear that facilitates efficient (rapid) and effective (forceful) motor action. One theory explaining this is the red light has an active effect in a short time interval through the visual processing pathway and decays with time (Katsuura et al., 2007; Huang et al., 2012). The light exposure time in this case is the crux of the whole argument. We interpret the reason as an impact of temporal distance. The exposure time of the present study was longer than that of previous studies. Red as a threat cue in achievement contexts may have a time restriction. This view is consistent with the study by Payen (2011).

The light power as an influence factor is likewise important. In the present research, we compared two different intensities of blue light. We found that the time interval of a

subject's self-exerted muscular power tended to be faster under a high-intensity light condition (blue I) than under a low-intensity light condition (blue II) (Figure 4-5). Thus, the light intensity may be important in influencing the will of subjects. As for the arousal level, the effect of a high-intensity light condition (blue I) may be inhibited if it is too powerful in comparison to the light exposure environment. It has been reported that the direct effects of light are not limited to physiologic variables but also include neurobehavioral performance measures such as alertness and reaction times (Badia et al., 1991; Campbell and Dawson, 1990). The two results in the present study lead to speculation that the light intensity could affect the subjective activeness with an approximate linear relationship under dim light conditions. However, the cognitive activity will be more sensitive to the light intensity and the threshold is lower to make a change in the arousal level.

The results of background EEG in alpha band power ratio showed that the values of blue II light condition were larger than the red light condition at Fz and Cz. This result indicated the arousal level based on the background EEG is higher in red light condition than in the blue II light condition. However, the results of event-related potentials P300 showed that the response time in blue II tended to be significant smaller than in red light conditions. The amplitude values in blue II tended to be significant larger than in red and blue I light conditions at C4. Those results of P300 indicated the cognitive level in blue II tended to be significant larger than red condition. The difference results between background EEG and the event-related potentials may indicated the color light of red which considered having an accelerate effect will come to decrease with the elapse time. However, the blue light will play a role to increase the brain arousal level with a long time light exposure.

4.5. Conclusions

Until now the main purpose of indoor lighting has been to aid visually directed tasks in the absence of sufficient external light. There is, however, increasing evidence to suggest that the brightness and wavelength of ambient light is not only important for task completion, but that it can also have strong non-visual biological effects, regulating the human circadian system and impacting the biological clock, mood and alertness. In the present study, the results of muscle measurement task indicated an actual similarity in finger adduction strength across different light exposure conditions. The findings give clear support to those studies that have found no relationship between viewed color and strength (Keller and Vautin, 1998, etc.).

However, in consideration of the results that time interval in the muscle measurement task tended to be longer in the blue II than blue I light condition, we conceive the light intensity may affect the subjective willing of the muscle strength output. This result may help to further determine the light illumination design to raise efficiency.

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Chapter 5

The effects of monochromatic light on muscle fatigue recovery

5.1. Background

In common parlance, ‘‘fatigue’’ is a term used to describe the decrease in physical performance associated with an increase in the real and/or perceived difficulty of a task or exercise. During muscle exercise, fatigue is defined as the inability to maintain the required level of strength (Edwards, 1981). Muscle fatigue is a very complex phenomenon in which multiple sites fail during muscular work. The underlying causes of fatigue fall into one of two categories: mental (neuromuscular—the central nervous system) and physical (peripheral—the actual muscle site) fatigue (Figure 5-1). Many physiological mechanisms are perturbed before the body feels the effect of fatigue and these changes sometimes constitute advance warning of fatigue.

The physiological processes involved in muscle force generation extend to the whole neuromuscular system. Many different factors may underlie and/or be involved in the expression of neuromuscular fatigue. Moreover, the maintenance of submaximal strength over time results from facilitatory and inhibitory influences of neuromuscular origin. In fact, the neuromuscular system tries to compensate for the decrease in force generation by implementing a variety of nervous and muscle-related mechanisms, in order to delay the point at which the task can no longer be performed.

What cause the fatigue? During the performance of maximal or submaximal muscle exercise, the decrease in force generation is caused by several different physiological phenomena (Place et al., 2010). Hence, ‘‘central fatigue’’ designates a decrease in voluntary activation of the muscle (i.e. a decrease in the number and discharge rates of the motor units (MUs) recruited at the start of muscle force generation), and ‘‘peripheral fatigue’’ indicates a decrease in the contractile strength of the muscle fibers and changes in the mechanisms underlying the transmission of muscle action potentials (Gandevia, 2001). These phenomena occur at the nerve endings and at the neuromuscular junction (NMJ) and are usually associated with peripheral fatigue.

The central nervous system (CNS) acts much like an automobile engine regulator. Most cars are made with a regulator that causes them to "shut down" when the engine revs too high for too long. This mechanism protects the engine from "over-heating." In the same way, our brains attempt to protect our muscles from tearing by reducing the rate nerve impulses are sent to our working muscles. In most cases, you'll experience central fatigue before local fatigue. In other words, when you think you simply can't do any more work because you're so fatigued, essentially what's happening is your mind is telling your body (muscles) to shut down. But in fact, you're probably able to continue for another couple of reps.

Local fatigue is related to local factors that limit the ability to perform muscular work. These include the energy systems (ATP-CP, glycolysis, and oxidation); the accumulation of metabolic byproducts (such as lactic acid); and the failure of the muscle fiber's contractile mechanisms. The energy systems act much the same way as fuel in a car or a battery in a flashlight. However, humans are different in that we have three energy systems within the muscle's cells that are called upon at different times depending on the intensity and duration of an activity.

The first energy system is called the ATP-CP system and is called upon during extremely short and intense bouts of exercise (e.g., weight training, sprinting, and jumping). It works by repeatedly breaking down ATP (the basic currency of energy in the body) and rebuilding ATP using CP (creatine phosphate). During repeated maximal contractions, fatigue coincides with CP depletion.

The other two energy systems are called into play during exercises that last longer than 30 seconds. Known as anaerobic (or glycolytic) and aerobic (or oxidative), these energy systems are very dependent on the availability of glycogen (the stored form of glucose—sugar). As with CP use, the rate of glycogen depletion is controlled by the intensity (i.e., how hard you train) of the exercise.

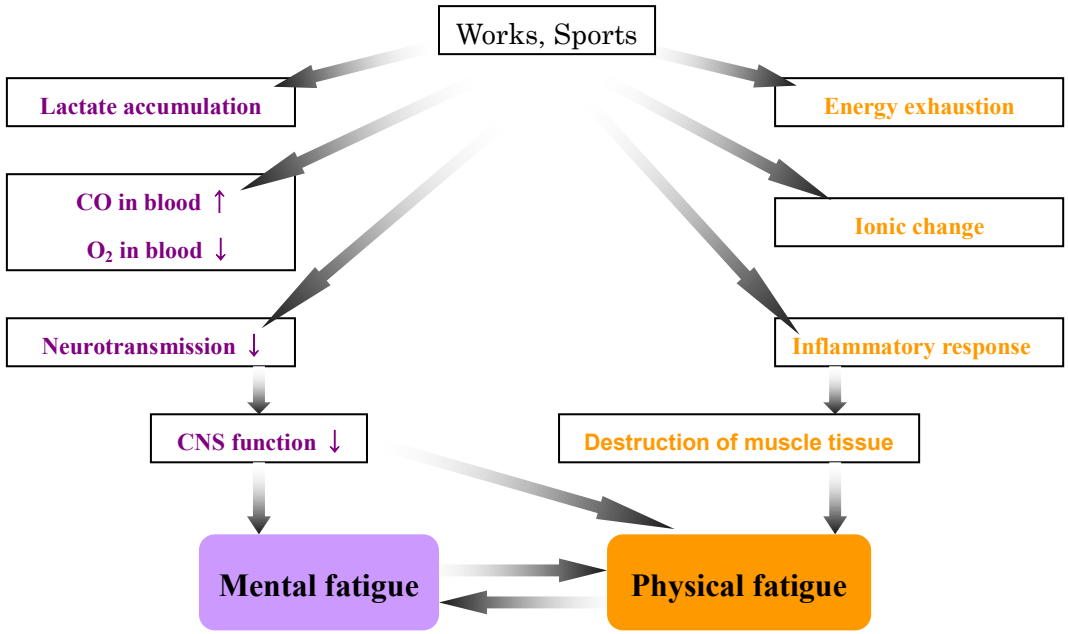


Figure 5-1. The mechanism of fatigue.

During sustained contractions, muscles progressively become less able to perform as well as at the beginning of the application of the force. The phenomenon of muscle fatigue is possible to quantify this process in a noninvasive way by monitoring the associated neuromuscular activation which is manifested in the surface EMG signal (DeLuca, 1984, Georgakis et al., 2003). Indeed, the spectrum of the EMG undergoes a compression-like change during the course of a muscle contraction and this behavior can be measured by introducing appropriate descriptors of the alteration. To this end, spectral variables are typically used to track the spectral shift against time. The mean (MNF) and median (MDF) spectral frequencies have been the most popular such variables both in academic studies and in clinical practice owing to their relevance to underlying physiological processes that control fatigue. For example, the initial value of MDF has been associated with the distribution of the muscle fiber type recruited, while its rate of change has been linked to the fatigability properties of the active motor units (Farina et al., 2003).

Research in evolutionary biology and psychology indicates that color is not only an aesthetic stimulus, but also carries important meaning. Red is the color that has received the most research attention. In human and non-human primates alike, red is associated with threat and danger. For example, red on the face of a competitor may likewise indicate testosterone-fueled anger or aggressiveness (Drummond, 1997), furthermore, red is used in student evaluation to indicate mistakes, in language to represent negative situations (e.g. “in the red”), and in traffic signals, alarms, and sirens to indicate impending danger. The clear parallels across phylogeny in the signal value of red suggest a biologically engrained link between red and danger in humans that is bolstered and broadened by societal learning (Elliot et al., 2007). Given the associative link between red and danger, it is not surprising that experiments have shown that red evokes avoidance motivation and behavior in human participants in achievement situations. Viewing red, relative to other chromatic and achromatic colors, prior to an achievement task produces an increase in right frontal cortical activation (Elliot et al., 2007) and an increase in local perceptual focus (Maier et al., 2008), both indicative of avoidance motivation (Davidson, 1992; Derryberry and Reed, 1994). Perceiving red also leads to the selection of easy rather than moderately challenging test items, less knocking on the door of a room where a test will be taken, and subtle postural movement away from an anticipated test (Elliot et al., 2007, 2008).

In this chapter, we investigated the effect of red, green and blue light exposure on the muscle fatigue and its recovery by a muscular strength task. Moreover, we recorded the change of muscle power and the EMG characteristics to inspect the recovery effects.

We anticipated that the red light will affect the muscle performance of producing large forceful responding. Critically, we conducted our research using precisely controlled color intensity manipulations. We recorded the physiological indices of the activities of the central nervous system by EEG, P300 and the muscle performance by EMG, MDF and force values.

5.2. Methods

5.2.1. Subjects

Six healthy young adult male volunteers, age 25-27 years, participated in the present study. They were sufficiently informed about the experimental procedure and gave written informed consent for study participation. To avoid muscle fatigue that could lead to biased torques, participants were instructed to refrain from participating in any rigorous physical activity or consuming alcoholic drinks or caffeine-containing food during the 24 h preceding the experimental session.

5.2.2. Measurements

5.2.2.1. General procedures

Twenty-five monochromatic light-emitting diode (LED) lights were set in front of subjects. To ensure even illumination, we put a filter between the light source and the subjects. We standardized measurement units to verify the different unit effects in the following classification: illuminance (red, green and blue I) and irradiance (red and blue II). The spectral distribution curves are shown in Figure 5-2. The color diagram is shown in Figure 5-3. The illuminance and irradiance of the four light conditions are shown in Table 5-1. Before the experiment, fluorescent lamps (5700 K) in a climatic chamber (25 ℃, 50% relative humidity) were turned on to stabilize the illuminance (312 lx).

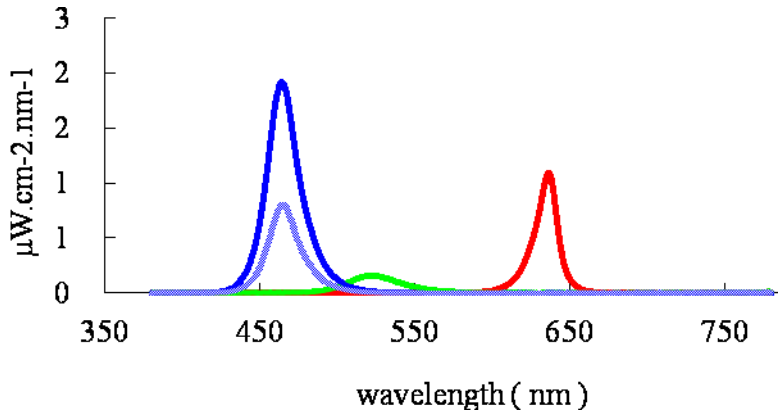


Figure 5-2. Spectral distribution curves of the red (—), green (—), blue I (—) and blue II (‥) light conditions.

Table 5-1. Illuminance and irradiance of red light, green light, blue I light and blue II light conditions.

Illuminance (photopic-lx)		Irradiance (μWcm^{-2})
red light	37	22
green light	36	6
blue I light	38	52
blue II light	17	24

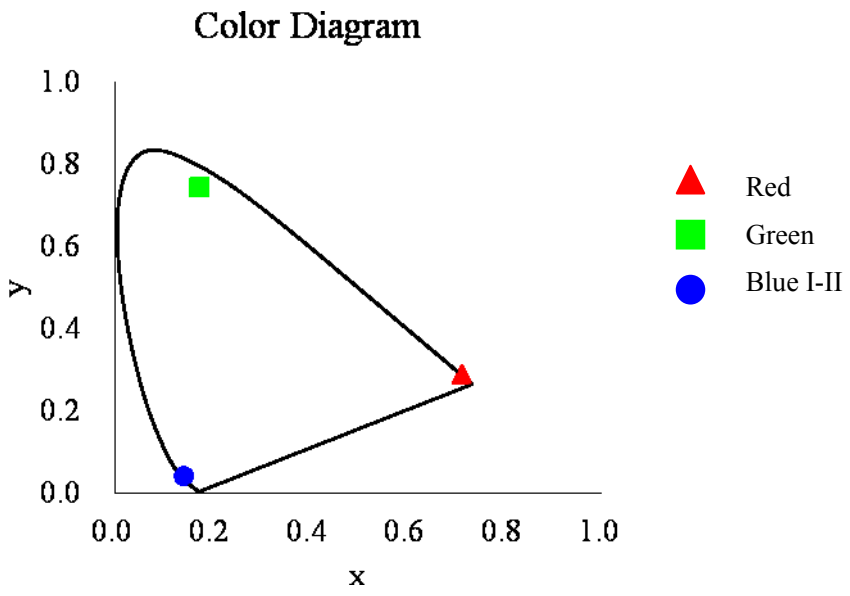


Figure 5-3. Color Diagram of the red, green and blue I-II light conditions.

In the experiment, each subject entered the climatic chamber and sat on a comfortable chair quietly for 30 min to get accustomed to the surroundings. During the 30 min we attached EEG and EMG electrodes. Subsequently, we adjusted the subject's position and fixed the right arm on the experimental setup as shown in Figure 5-5. Next, the fluorescent lamps were turned off, and then the monochromatic lights were turned on and stayed on until the experiment ended. After one hour of light exposure, each subject performed a fatigue task and underwent recovery period afterward. During the experiment, we examined each subject's EEG, P300 and EMG results. The experimental protocol is shown in Figure 5-4. The four light conditions (red, green, blue I and blue II) of the experiment were conducted during the same hours (13:00-15:00) but on separate days. To consider the influence of the experiment day compared to the next day, the interval between each two sets of conditions was at least 3 days. The order of color conditions was counterbalanced among the subjects.

5.2.2.2. Fatigue task

After 60 minutes of light exposure, each subject performed three self-regulated sessions of intermittent isometric maximal voluntary contraction (MVC). Each session contained forty trials of MVC. The interval between each set of two trials was confined to less than 30 seconds, and all the subjects were asked to memorize the chosen selective interval that they performed at the beginning and repeat it in the subsequent experiment sessions as consistently as they could. At the end of each session, the subject was asked to completely relax the index finger for 1 min, and during the rest time, the subject was asked to provide a subjective assessment, using his left hand, of the effort level of the right hand, to make sure the subject had made the best effort during each period.

5.2.2.3. Recovery Period

After the fatigue task, the subjects were asked to completely relax and have a rest on the chair. During the recovery period, subjects were asked to do contraction tests at 1, 3, 5, 7, 10, 15, 20, 30 min once to examine the degree of recovery.

5.2.2.4. Recordings

The right hand was positioned in an apparatus where the wrist and fingers, except the index finger, were constrained (Figure 5-5). The index finger was free to move in the horizontal plane. A piezoelectric force transducer (TECA SA-30A) was in contact with the first phalanx of the index finger.

The surface EMG signals were recorded from the first dorsal interosseous (FDI) muscle abduction in the right hand. A bipolar electrode (Biopac, Inc., USA, TSD150B, Ag/AgCl, diameter 11 mm, inter-electrode distance 20 mm and a bandpass of 12 to 500 Hz) was positioned on the muscles, which were identified by palpating the skin when subjects flexed and extended the fingers after skin abrasion and cleaning the skin with alcohol. A reference electrode was placed on the skin overlying the back of the left wrist. One second of EMG recordings was obtained before and after fatigue, together with the corresponding power spectra, as shown in Figure 5-9. The electrode was taped onto the skin firmly to reduce movement artifacts and remained in place throughout the study.

To determine the cortical correlate of the muscle activities, we recorded electric potentials at the Fz, C3, Cz and C4 recording sites based on the International 10/20 system (Nihon Kohden, Inc., Japan, NE-113A, Ag/AgCl, diameter 9 mm and a

bandpass of 0.032~60 Hz). The reference electrodes (A1 and A2) were on the earlobes. The ground electrode was on the forehead. An electrooculogram (EOG) (the same bandpass as that for the EEG) was recorded to exclude segments with eye movement artifacts. To evaluate the cognitive function, we elicited the P300 component of the event-related brain potential was elicited by an auditory "oddball" paradigm.

All the data were recorded at a sampling rate of 1000 Hz on a laptop computer by a data acquisition system (Acqknowledge 3.9.1, Biopac Systems, Inc.).

In the psychological evaluation, we used visual analogue scales (VAS) to assess feelings of arousal level, muscle fatigue, muscle strength, muscle force output effortful level, stress and concentration in the baseline condition and at the end of the experiment. Feelings about the favorite light condition and brightness of light condition for each condition were asked only at the end of the experiment.

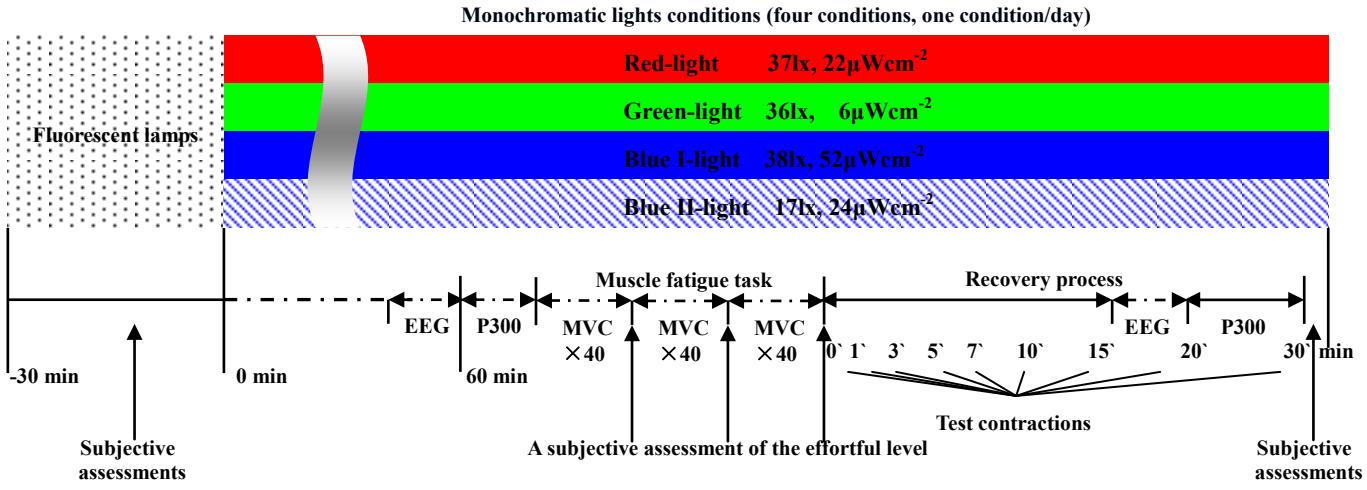


Figure 5-4. The experimental protocol. After one hour light exposure, the subjects were asked to perform three sessions of intermittent isometric MVCs. The EEG and the EMG single were recorded during the experiment. The subjective assessments were asked in initial and final stage of the experiment.

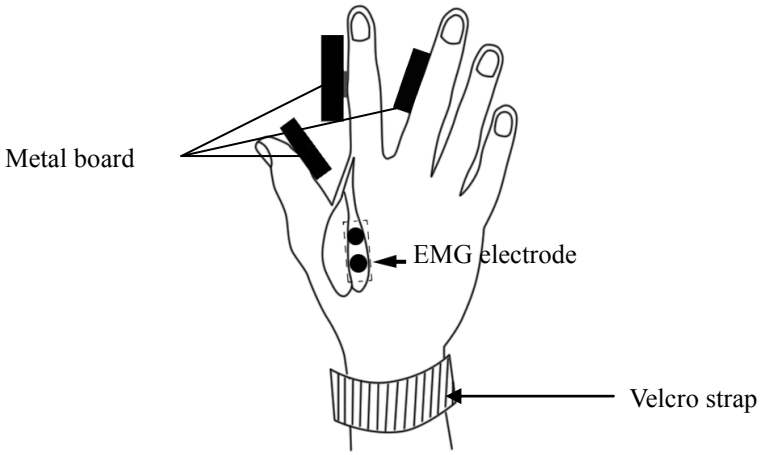


Figure 5-5. Schematic drawing of the experimental set-up. The right hand is constrained at the wrist level. The index finger is placed in an anatomical support and a piezoelectric transducer measured force. Forward hand shift is avoided with a constraint at the thumb. The index support and all constrains are adjustable in position to adapt to the anatomy of the subject.

The surface EMG signals were recorded from the first dorsal interosseous (FDI) muscle abduction in the right hand. A bipolar electrode (Biopac, Inc., USA, TSD150B, Ag/AgCl, diameter 11 mm, inter-electrode distance 20 mm and a bandpass of 12 to 500 Hz) was positioned on the muscles, which were identified by palpating the skin when subjects flexed and extended the fingers after skin abrasion and cleaning the skin with alcohol. A reference electrode was placed on the skin overlying the back of the left wrist. One second of EMG recordings was obtained before and after fatigue, together with the corresponding power spectra, as shown in Figure 5-8. The electrode was taped onto the skin firmly to reduce movement artifacts and remained in place throughout the study.

To determine the cortical correlate of the muscle activities, we recorded electric potentials at the Fz, C3, Cz and C4 recording sites based on the International 10/20 system (Nihon Kohden, Inc., Japan, NE-113A, Ag/AgCl, diameter 9 mm and a bandpass of 0.032~60 Hz). The reference electrodes (A1 and A2) were on the earlobes. The ground electrode was on the forehead. An electrooculogram (EOG) (the same bandpass as that for the EEG) was recorded to exclude segments with eye movement artifacts. To evaluate the cognitive function, we elicited the P300 component of the event-related brain potential by an auditory "oddball" paradigm (1000-Hz standard sound-80% and 2000-Hz target sound-20%, 65 dB SPL auditory stimuli by an earphone).

All the data were recorded at a sampling rate of 1000 Hz on a laptop computer by a data acquisition system (Acqknowledge 3.9.1, Biopac Systems, Inc.).

In the psychological evaluation, we used visual analogue scales (VAS) to assess feelings of arousal level, muscle fatigue, muscle strength, muscle force output effortful level, stress and concentration in the baseline condition and at the end of the experiment. Feelings about the favorite light condition and brightness of light condition for each condition were asked only at the end of the experiment.

5.2.3. Data analysis

An analysis of variance (ANOVA) was computed for each dependent variable: maximal voluntary electrical activity (MVE), the spectral shift of median frequency (MDF), alpha wave band power ratio (EEG), amplitude, latency and response time of P300, and subjective assessment.

The red light, green light and blue I light conditions were classified as illuminance, which was approximately 37 lx; the red light and blue II light conditions were classified in irradiance, which was approximately 23 μWcm^{-2}. The blue I light and blue II light conditions were from the same light source; however, the power of the blue II light condition was half that of the blue I light condition.

%MVE:

The MVE values were defined to assess the maximal forceful exertion of muscle performance in the muscle fatigue task. The %MVE values for the FDI muscle were calculated for a normalization procedure. In this processing, the raw data were first processed into the root mean square (RMS). Two hundred samples RMS-converted signals were plotted. Afterwards the EMG signals collected during FDI muscle abduction were expressed as percentages of the calculated mean RMS of MVE (%MVE). We used a two-way repeated-measures ANOVA (color×order 2) in the three color groups on the mean values of %MVE in every session of muscle fatigue task.

MDF:

The MDF had been used in determining muscle fatigue responses during recovery. For the frequency analysis, the power spectrum was calculated for each trial and the MDF (the frequency where the power of the FFT-derived power spectrum is halved) was calculated. We used a one-way repeated-measures ANOVA in the three color groups and a paired t-test in the other two color groups.

EEG:

We calculated the alpha wave band power ratio (alpha / (alpha † beta) ratio, alpha band as 8~13 Hz, beta band as 13~30 Hz). A two-way repeated-measures ANOVA (color×time) was used in the three color groups at Fz, C3, Cz and C4.

P300:

A two-way repeated-measures ANOVA (color×time) was conducted on the amplitude and the latency of P300 in the three color groups at Fz, C3, Cz and C4.

Subjective assessments:

A two-way repeated-measures ANOVA (color×order 1) was conducted in the three color groups on feelings of arousal level, muscle fatigue, muscle strength, muscle force output effort level, stress and concentration. A one-way repeated-measures ANOVA 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. To assess participants' sense of the brightness of each light condition, which was only asked after light exposure, we used a one-way repeated-measures ANOVA in the red, green and blue I group and a paired t-test in the red, blue II group and the blue I, blue II group.

The time factor means the time of light exposure measured in 58~60 min light exposure and in 18'~20' min of recovery (shown in Figure 5-4). There are two order factors, one signified as order 1, the other signified as order 2. The order 1 factor indicates that the order before and after the experiment. The order 2 factor indicates the order of the three trials in the muscle fatigue task.

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 a statistically significant trend was set at 0.1.

5.3. Results

MVC assessment had been excluded as measure miss of two subjects. Instead of the MVC data, we used the time interval between trials in the fatigue task and the MVE data to assess the motor performance.

5.3.1. Electrophysiological data

%MVE:

The order 2 main effect tended to be significantly different in the red, green, blue I group ($p=0.016$) compared to the other groups. The time period 1 was significantly larger than time period 2 ($p=0.032$), and likewise was larger than time period 3 ($p=0.053$). Figure 5-6 shows all six subjects' EMG results during the fatigue task performance under the green light condition. No significant difference was found in the red, blue II group or the blue I, blue II group. During the recovery period, there were no significant differences among the three color groups; however, in the early part of the recovery (at 3 min and 5 min), a trend toward significant difference was found in the blue I, blue II group (Figure 5-7).

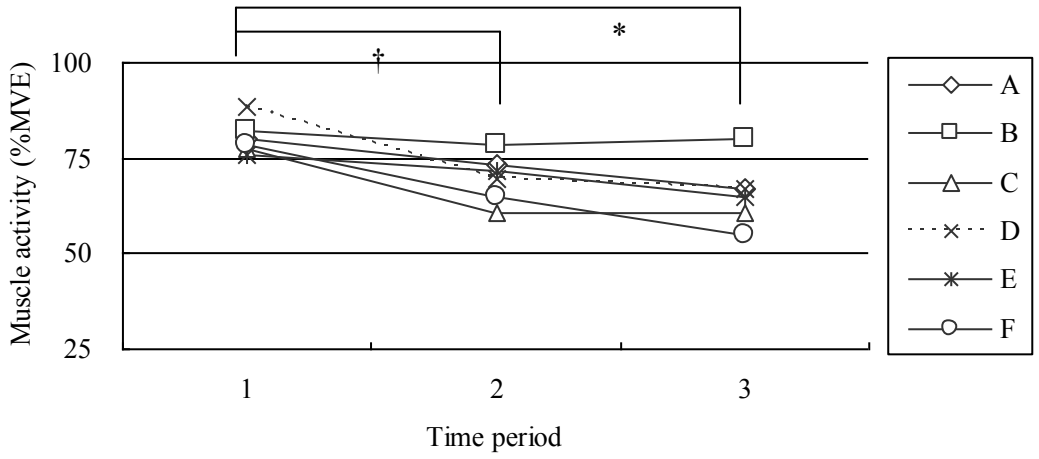


Figure 5-6. Mean voluntary EMG electrical activity of all six subjects during the fatigue task (1, 2, 3) performance in green light condition. (†, $p<0.1$; *, $p<0.05$)

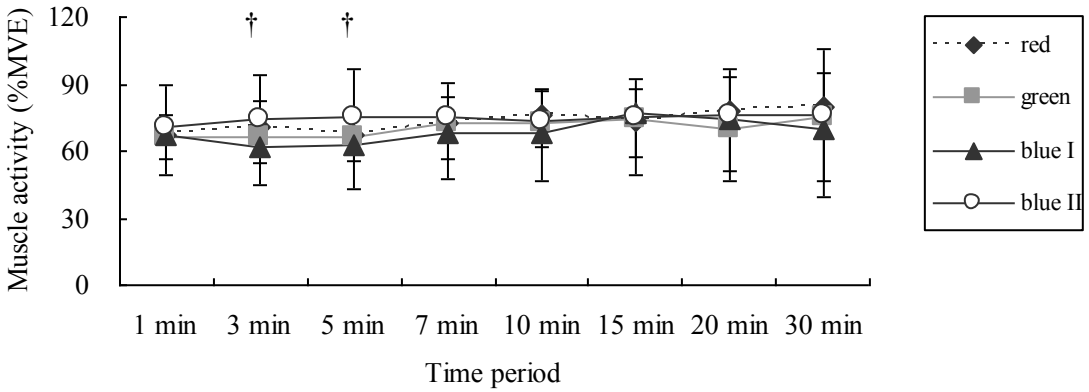


Figure 5-7. Mean voluntary EMG electrical activity during the recovery progress in four light conditions. Only the blue I and blue II group showed a trend significant difference at 3 min ($p=0.054$) and 5 min ($p=0.064$). (†, $p<0.1$)

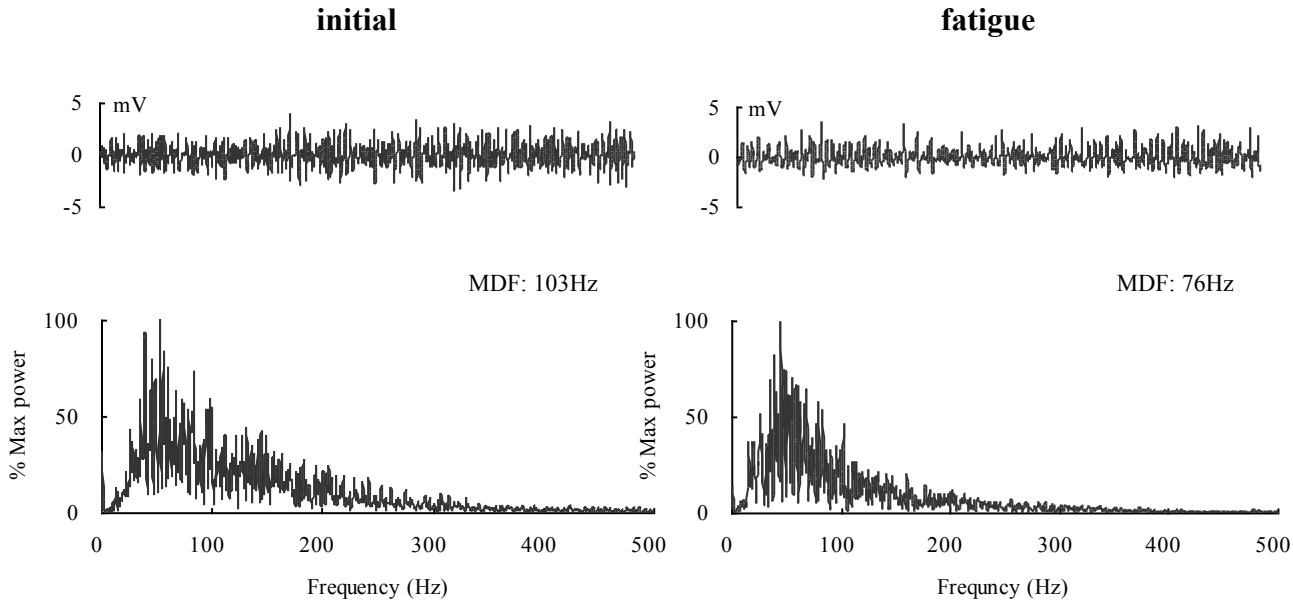


Figure 5-8. Typical sets of computer outputs showing raw EMG data of one subject in the red light condition, and corresponding normalized power spectra, calculated median frequency (MDF) at the beginning (initial) and the end (fatigue) of muscular isometric maximal voluntary contractions.

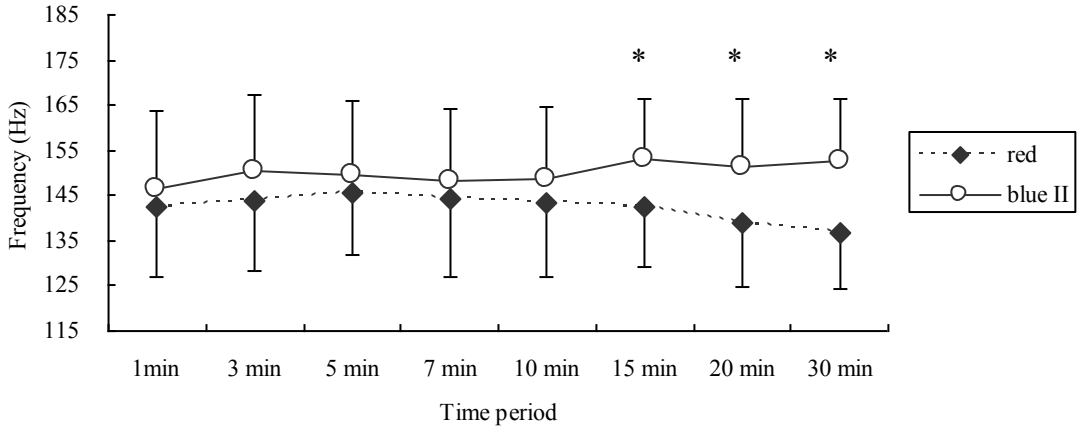
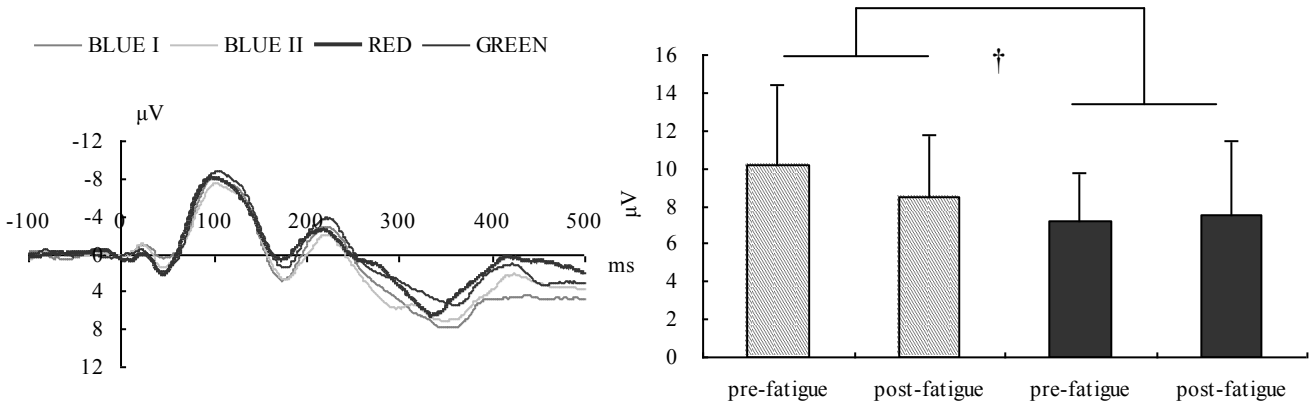


Figure 5-9. The values of MDF in the red-light and blue II-light condition group. The values significantly became larger at 15 (p=0.013), 20 (p=0.044) and 30 min (p=0.011) in the blue II than the red light condition. (*, p<0.05)

P300:

No significant difference was found in the response time or the latency of P300 in the three color groups. However, the amplitudes of P300 at C4 tended to be significantly larger under the blue II condition compared to the red light condition (p=0.071) (Figure 5-10).



(a) (b)

Figure 5-10. (a) The grand averaged P300s at C4 in all four color-light conditions after muscle training. (b) The amplitudes of P300 at C4 tended to be significantly larger in blue II light (□) than red light (■) condition (p=0.071). (†, p<0.1)

EEG:

The color × time interaction in the red and blue II light group was significant. Follow-up tests showed the values of alpha wave band power became significantly larger after the muscle fatigue task under the red light condition but not under the blue II light condition (p=0.044) (Figure 5-11).

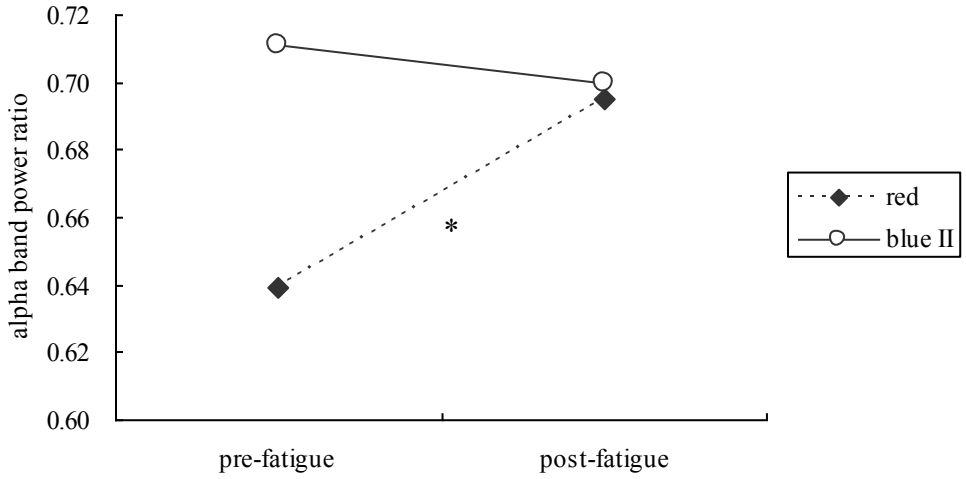


Figure 5-11. The values of alpha wave band power before and after the fatigue task. The values became significantly larger after muscle fatigue task in red light condition (p=0.044), however, no significantly different was found in blue II light condition. (*, $p<0.05$)

Subjective assessments:

There was no significant difference of color effects on the feelings of arousal level, muscle fatigue, muscle strength, muscle force output effort level, stress and concentration. Some questions showed a periodical significant difference without color effect.

5.4. Discussion

The present study aimed to investigate the effect of different monochromatic lights on muscle fatigue and recovery. Motor performance was assessed by %MVE and MDF. The brain arousal level was assessed by EEG and P300.

The MVE values were significantly different among time periods 1, 2 and 3 (Figure 5-6). However, no significant difference was found among the color conditions. Only a slight difference was found between the blue I and blue II group and the other groups in the initial part of recovery (Figure 5-7). These results indicated that after one hour of light exposure, little significant difference in muscle performance was found base on the color effect. Several studies have highlighted the danger or threat effect of red (Payen et al., 2011; Elliot and Aarts, 2011). These studies proposed that the immediate, urgent response to red may be a subcortically based “call to arms” involving fear that facilitates efficient (rapid) and effective (forceful) motor action. One theory explaining this is the red light has an active effect in a short time interval through the visual processing pathway and decays with time (Katsuura et al., 2007; Huang et al., 2012). The light exposure time in this case is the crux of the whole argument. We interpret the reason as an impact of temporal distance. The exposure time of the present study was longer than that of previous studies. Red as a threat cue in achievement contexts may have a time restriction. This view is consistent with the study by Payen (2011).

In the present study, the MDF results of EMG showed that the blue II light condition was significantly more effective in promoting recovery than was the red light condition beginning 15 min after the end of the muscle fatigue period (Figure 5-9). The rate change of MDF has been linked to the fatigability properties of the active motor units (Farina et al., 2003). As such, the EEG and P300 results indicated that the blue light maintains the brain arousal level (Figure 5-10, 5-11). This may indicate that the blue light inhibits the decrease of synaptic transmission in the motor area during the muscle recovery period.

The performance of blue light is probably supported by the non-image-forming effects related to the ipRGCs, which have been demonstrated in previous studies to increase the brain arousal level (Lockley et al., 2006; Lee et al., 2008; Katsuura et al., 2012). The recent discovery of 'non-visual' retinal receptors has confirmed an anatomical basis for the observed biological effects of light, with the photopigment melanopsin playing an essential role in phototransduction (Berson et al., 2002). As such, light has a broad regulatory impact on human physiology within virtually all tissues in the body, with action spectra in humans showing the peak sensitivity for these effects to be in the short

wavelength portion of the spectrum (Thapan et al., 2001). Several studies also found blue light effects on the arousal level. The narrow-bandwidth blue light outperforms dimmer red light in reversing symptoms of major depression with a seasonal pattern (Glickman et al., 2006). An exposure of office workers to blue-enriched white light during daytime work hours improves subjective alertness and performance, and reduces evening fatigue (Viola, 2008).

The light intensity as an influence factor is likewise important. In the present research, we compared two different intensities of blue light. We found that the %MVE for muscle activity showed a slightly difference in blue I and blue II light conditions at 3 min and 5 min during the recovery progress. Thus, the light intensity may affect the muscle strength output or recovery. As for the arousal level, the effect of a high-intensity light condition (blue I) may be inhibited if it is too powerful in comparison to the light exposure environment. It has been reported that the direct effects of light are not limited to physiologic variables but also include neurobehavioral performance measures such as alertness and reaction times (Badia et al., 1991; Campbell and Dawson, 1990). In the present experiment, only the blue II light condition showed superiority to the red light condition, although the blue II have a double light intensity power to blue I, there was no significant difference between red and blue II light conditions in the brain arousal test. The results may lead to speculation that the light intensity may have an inverted U-shaped under dim light conditions on the brain arousal level.

5.5. Conclusions

Until now the main purpose of indoor lighting has been to aid visually directed tasks in the absence of sufficient external light. There is, however, increasing evidence to suggest that the brightness and wavelength of ambient light is not only important for task completion, but that it can also have strong non-visual biological effects, regulating the human circadian system and impacting the biological clock, mood and alertness. In the present study, we found that exposure to short-wavelength light could expedite muscle recovery by promoting the synaptic transmission in the motor area. The short-wavelength light (blue) have been demonstrated to keep the central nervous system function at a higher level than the other color light through a non-visual pathway which associated with the new photoreceptor of ipRGCs. We suggest that this effect also worked in a muscle fatigue recovery period.

Testing the efficacy of these wavelength regions in the strength test and during recovery may help to further determine the optimal wavelength for light illumination or spectral composite illumination. Several significant results were found in the present study. Larger scale studies with other comparison conditions (e.g., narrow bandwidth blue, green and red lights of equal photon density compared to broad spectrum white light) need to be completed to determine the potency of narrow-band short-wavelength light relative to current standard conditions.

This research establishes a link between blue color and basic motor output, and highlights the importance of recovery. This may suggest that the participants subjected to blue light derived more benefit from treatment than did the participants subjected to red light with comparable expectations.

Further research is necessary to directly document the neural pathways through which blue light exerts its influence on motor output. We will conduct a functional MRI-measured cortical activation study to investigate the relationship between the wavelength effect and the fatigue recovery in the motor area.

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Chapter 6
General Discussion

In this article, we have investigated the effect of monochromatic light on time perception and muscular performance of the muscular strength and its fatigue recovery. Several indexes are used in series of experiments, such as EEG, VEP and P300 for the central nervous system assessment; PPG for the automatic nervous system assessment; EMG, MVE and MDF for the peripheral muscle activities assessment; task performance recording and subjective questionnaire scores for the psychological assessment. The main results obtained by this research are as follows.

In Chapter 2, the repeatability of VEP was investigated. The results indicated a high success rate of VEP. Moreover, each VEP component of the ERP was analyzed to investigate the relationship to the color information process. The results indicated VEP components transmit the chromatic information to inferior temporal cortex. The findings were considered that by studying the component of VEP which induced by chromatic transient flash stimuli, it is not only for confining to examine a normal neurological vision about the visual cortex, but also extended to the visual information pathway after visual cortex as one of the evoked potential. There also has a finding about the light intensity effects which showed a difference on amplitude of P200in the frontal and occipital lobe. The result indicated a possibility which light intensity may affect the brain cognitive level.

In Chapter 3, the time sense in different monochromatic light conditions was compared by time production task of 180 s and time estimation task of 600 s. The results indicated that color effect had a meaningful connection with the time perception. The red color may have an acceleration effect to make time perceived faster than other color conditions. However, the result also indicated this acceleration effect of red color light decreased with the elapse of time.

In Chapter 4, the muscle strength output was investigated by a muscle measurement task in different monochromatic light conditions. Although several previous studies proposed that the immediate, urgent response to red may be a subcortically based ‘call to arms’ involving fear that facilitates efficient and effective motor action, the results of our research indicated that after one hour light exposure, little significant difference in muscle performance was found with the color effects. In addition, the inconformity of the results on background EEG and P300 indicated the cognitive level will be higher in the blue light condition although the background EEG still dominated in the red light condition. These results may be explained that red light has an active effect in a short time interval. However, the reinforced effect will decay with time, and the blue light will play a role to increase the brain arousal level with a longer time light exposure.

In Chapter 5, the muscle fatigue and recovery performance were investigated in different monochromatic light conditions. The MDF results of EMG showed that blue light condition was significantly effective in reliving recovery than the red light condition from 15 min after muscle fatigue task. As such, the central nervous system indexes of EEG and P300 showed the blue light has an effect to keep brain on a higher arousal level than red light condition. This research may reveal that the blue light could keep the central nervous system function at a high level such like inhibit the decrease of synaptic transmission in the motor area during the muscle recovery period.

The main results of each chapter on color effects are shown in the table below.

	Index	Main results on color effects	
Chapter 2	VEP(N1)	Amplitude	×
		Latency	F, C > P, O (R, G and B) (∗)
	VEP (P1)	Amplitude	R > G and B > G (†)
	VEP (N2)	Amplitude	R < G, R < B and G < B (∗)
	VEP (P2)	Amplitude	R < G, B (∗)
		Latency	F, C < P, O (R, G and B) (∗)
	N1 and P2	High repeatability	
Chapter 3	Time task	T180 task	Time pass: R < G, BI, II (∗)
		T600 task	Time pass: R < G, BI, II (†); G < BI (∗)
	Response time	R > BII (†)	
	EEG (alpha)	△G < △BI (∗) (C3); △BI < △BII (∗) (Fz, Cz)	
	P300	Amplitude	R < BII (†) (C4)
		Latency	×
	PPG	G < BI (†); BI > BII (†)	
	Subjective assessments	Eyestrain	△R < △BII (∗)

×: no significance

†: $p < 0.1$

∗: $p < 0.05$

△: the values changed to the baseline condition

	Index	Main results on color effects	
Chapter 4	Time interval in fatigue task	BII > BI (†)	
	%MVE	×	
	EEG (alpha)	R < BII (Fz, †; Cz, ∗)	
	Response time	R > BII (†)	
	P300	Amplitude	R, BI < BII (†)
		Latency	×
Chapter 5	%MVE	Recovery time 3, 5 min, BI < BII (†)	
	MDF	Recovery time 15, 20, 30 min, R < BII (∗)	
	EEG (alpha)	After fatigue, △R > △BII (∗)	
	P300	Amplitude	R < BII (†)
		Latency	×

×: no significance

†: $p < 0.1$

∗: $p < 0.05$

△: the values changed after fatigue task

In this paper, we hypothesized that long wavelength color (red) light may have an acceleration effect on the initial stage of cognition. 'Immediately, strongly' is the description to the red color light effect. Meanwhile, the short wavelength color (blue) light may have a slowing and lasting effect during the light exposure period, and extend over the next a few hours. This effect of blue color light is established by a number of studies on the new photoreceptors of ipRGCs about the non-visual system which is demonstrated that short-wavelength light could increase the brain arousal level. We obtained some supports for our conceptualization from a series of experiments that manipulated two time perception tasks to examine whether the length of time interval affect the temporal information in different monochromatic light conditions. The results demonstrated our hypothesis. Red light make the time sense passed faster in a 180 s time production task, however, the significant difference get to be weak in a 600 s time estimation task. After one hour light exposure, an inconformity appeared between the

alpha band power ratio of background EEG and the P300 of ERPs. The difference may indicated the short-wavelength light (blue) will have the advantage with the time pass, and reflect to the cognitive level at first.

A manipulation of muscle strength task based on rigorous experimental methods provided reliable evidence for the color effects on the muscle strength output. The findings give clear support to those studies that have found no relationship between viewed color and strength output. This paper also found that the exposure to the short wavelength light could expedite muscle fatigue recovery. Most of the research on muscle strength is psychological study. Typically, the color stimuli setting are too optimistic. This study will be a good reference.

These findings possess point of penetration because previous studies showed an inconformity between the short-wavelength light (blue) and the long-wavelength light (red). Some studies indicated the blue light could increase the brain arousal level, some almost the psychological studies focused on the red color indicated a ‘call to arm’ effect which means the red color could make people increase their vigilance and response quickly. Questions here might arise about which side you will stand. Through this paper, I ventured a new viewpoint that makes a threshold value exist to the red and blue color as a critical point. The red color light has a short effect to accelerate the response and arousal level quickly and powerfully, however, this acceleration effect of red color light decreased with the elapse of time. The blue light has a long effect to increase the arousal level, however, the effect almost through a non-vision system slowly and weakly. Now the remaining question will be how long the will all the two color light keep their effect or where is the critical point to distinguish.

Although our research focused on perceived the difference of monochromatic light effects, it is still hard to sum up the result in one word to summarize the threshold value. The results of this paper may conclude the time point will shorter than one hour because the inconformity of EEG and the P300.

The light intensity is another important influence factor. Several results in this paper demonstrated the light power will affect the performance such like the self-exerted muscle strength, %MVE values in the recovery period. Moreover, the amplitude of evoked potential is very sensitive to the light intensity indicated the relationship between the cognitive activity and the light intensity.

In closing, we recognize that our results indicated a new viewpoint which may conduct the future study on color effects. With this in mind, the contributions of our findings lie not so much in providing comprehensive advice but in providing evidence that executional factors such as color affect perceived in muscle strength, time perception,

muscle fatigue and muscle fatigue recovery.

Before the field of light and lighting will be ready for such a revolutionary change, therefore, many steps should still be done, and many questions should find an answer. And, above all, a new theoretical approach for lighting is required to understand the role lighting practice can play for improving the design of the luminous environment basing on these discoveries.

In summary, inter-disciplinary research is urgently required on establishing the potential effects of different types of light on health, stress-levels, work efficiency, rehabilitation, and well-being. The correct types of illumination environment can be created.

Appendixes

A-1. EEG measurements

Electroencephalography is a medical imaging technique that reads scalp electrical activity generated by brain structures. The electroencephalogram is defined as electrical activity of an alternating type recorded from the scalp surface after being picked up by metal electrodes and conductive media.

The EEG measured directly from the cortical surface is called electrocortiogram while when using depth probes it is called electrogram. In this paper, we will only refer to EEG measured from the head surface. Thus electroencephalographic reading is a completely non-invasive procedure that can be applied repeatedly to subjects, and with virtually no risk or limitation.

When brain cells (neurons) are activated, local current flows are produced. EEG measures mostly the currents that flow during synaptic excitations of the dendrites of many pyramidal neurons in the cerebral cortex. Differences of electrical potentials are caused by summed postsynaptic graded potentials from pyramidal cells that create electrical dipoles between soma (body of neuron) and apical dendrites (neural branches). Only large populations of active neurons can generate electrical activity recordable on the head surface. Between electrode and neuronal layers current penetrates through skin, skull and several other layers. Weak electrical signals detected by the scalp electrodes are massively amplified, and then recorded on paper or computer. Due to capability to reflect both the normal and abnormal electrical activity of the brain, EEG has been found to be a very powerful tool in the field of neurology and clinical neurophysiology.

From the anatomical point of view, the brain can be divided into three sections: cerebrum, cerebellum, and brain stem. The cerebrum consists of left and right hemisphere with highly convoluted surface layer called cerebral cortex. The cortex is a dominant part of the central nervous system. The cerebrum obtains centers for movement initiation, conscious awareness of sensation, complex analysis, and expression of emotions and behavior. The cerebellum coordinates voluntary movements of muscles and balance maintaining. The brain stem controls respiration, heart regulation, biorhythms, neurohormone and hormone secretion, etc. The highest influence to EEG comes from electric activity of cerebral cortex due to its surface position.

The first brain electrical activity record was discovered in 1875 by an English physician Richard Caton who observed the EEG from monkeys' exposed brain. In 1924, a German neurologist named Hans Berger recorded the human brain electrical activities. Since then, a new measurement to study the functional status of brain set out.

Brain patterns form wave shapes that are commonly sinusoidal. Usually, they are measured from peak to peak and normally range from 0.5 to 100 μV in amplitude, which is about 100 times lower than ECG signals. By means of Fourier transform power spectrum from the raw EEG signal is derived. In power spectrum contribution of sine waves with different frequencies are visible. Although the spectrum is continuous, ranging from 0 Hz up to one half of sampling frequency, the brain state of the individual may make certain frequencies more dominant.

The best-known and most extensively studied rhythm of the human brain is the normal alpha rhythm. Alpha can be usually observed better in the posterior and occipital regions with typical amplitude about 50 μV (peak-peak). According to our experiences alpha was also significant between posterior and central regions in comparison to other regions. Alpha activity is induced by closing the eyes and by relaxation, and abolished by eye opening or alerting by any mechanism (thinking, calculating). Most of the people are remarkably sensitive to the phenomenon of “eye closing”, i.e. when they close their eyes their wave pattern significantly changes from beta into alpha waves. The precise origin of the alpha rhythm is still not known. Alpha waves are usually attributed to summated dendrite potentials. Evoked potentials (e.g. generated in brain stem) often consist of fiber potentials (axonal) and synaptic components. EEG is sensitive to a continuum of states ranging from stress state, alertness to resting state, hypnosis, and sleep. During normal state of wakefulness with open eyes beta waves are dominant. In relaxation or drowsiness alpha activity rises and if sleep appears power of lower frequency bands increase. A-3 will introduce the alpha band power ratio as a central nervous system index to examine the brain arousal level.

Various regions of the brain do not emit the same brain wave frequency simultaneously. An EEG signal between electrodes placed on the scalp consists of many waves with different characteristics. The EEG is typically described in terms of (1) rhythmic activity which usually call background EEG and (2) transients which usually called evoked potential EEG. The rhythmic activity is divided into bands by frequency. To some degree, these frequency bands are a matter of nomenclature (i.e., any rhythmic activity between 8–13 Hz can be described as "alpha wave"), but these designations arose because rhythmic activity within a certain frequency range was noted to have a certain distribution over the scalp or a certain biological significance.

There are several named wave patterns of cerebral signals observed in the scalp EEG falls in the range of 1-30Hz as shown as below.

Delta wave is the frequency range up to 4 Hz. It tends to be the highest in amplitude and the slowest waves. It is seen normally in adults in slow wave sleep. It is also seen

normally in babies. It may occur focally with subcortical lesions and in general distribution with diffuse lesions, metabolic encephalopathy hydrocephalus or deep midline lesions.

Theta wave is the frequency range from 4 Hz to 7 Hz. Theta is seen normally in young children. It may be seen in drowsiness or arousal in older children and adults; it can also be seen in meditation. This range has been associated with reports of relaxed, meditative, and creative states.

Alpha wave is the frequency range from 8 Hz to 12 Hz. Hans Berger named the first rhythmic EEG activity he saw as the "alpha wave". This was the "posterior basic rhythm" (also called the "posterior dominant rhythm" or the "posterior alpha rhythm"), seen in the posterior regions of the head on both sides, higher in amplitude on the dominant side. It emerges with closing of the eyes and with relaxation, and attenuates with eye opening or mental exertion. The posterior basic rhythm is actually slower than 8 Hz in young children (therefore technically in the theta range). In addition to the posterior basic rhythm, there are other normal alpha rhythms such as the mu rhythm (alpha activity in the contralateral sensory and motor cortical areas that emerges when the hands and arms are idle; and the "third rhythm" (alpha activity in the temporal or frontal lobes).

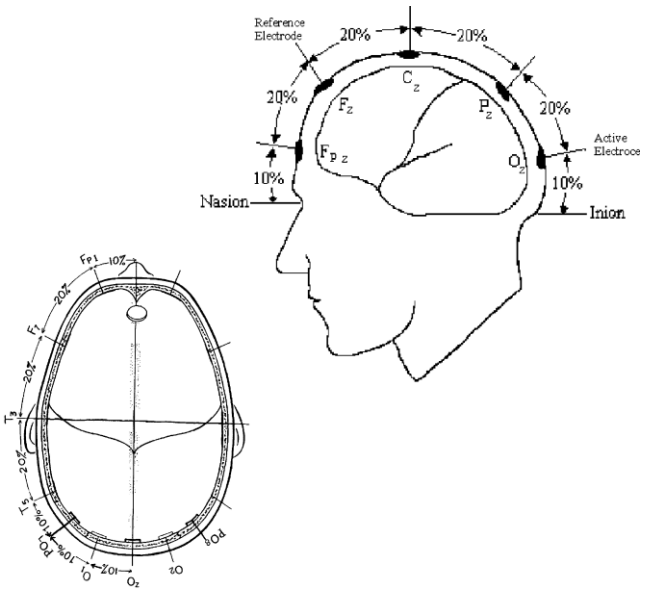
Beta wave is the frequency range from 13 Hz to about 30 Hz. It is seen usually on both sides in symmetrical distribution and is most evident frontally. Beta activity is closely linked to motor behavior and is generally attenuated during active movements. Low amplitude beta with multiple and varying frequencies is often associated with active, busy or anxious thinking and active concentration. Rhythmic beta with a dominant set of frequencies is associated with various pathologies and drug effects. It is the dominant rhythm in subjects who are alert or anxious or who have their eyes open.

Gamma wave is the frequency range approximately 30–100 Hz. Gamma rhythms are thought to represent binding of different populations of neurons together into a network for the purpose of carrying out a certain cognitive or motor function.

An evoked potential or evoked response is an electrical potential recorded from the nervous system of subjects following presentation of a stimulus. Evoked potential amplitudes tend to be low, ranging from less than a microvolt to several microvolts, compared to tens of microvolts for EEG, millivolts for EMG, and often close to a volt for ECG. To resolve these low-amplitude potentials against the background of ongoing EEG, ECG, EMG, and other biological signals and ambient noise, signal averaging is usually required. The signal is time-locked to the stimulus and most of the noise occurs randomly, allowing the noise to be averaged out with averaging of repeated responses. Signals can be recorded from cerebral cortex, brain stem, spinal cord and peripheral nerves. Usually the term "evoked potential" is reserved for responses involving either recording from, or stimulation of, central nervous system structures.

The VEP and P300 event-related potentials will be described in the following sections.

The scalp electrodes should be placed relative to bony landmarks, in proportion to the size of the head, according to the International 10/20 system (see Figure A-1). The anterior/posterior midline measurements are based on the distance between the nasion and the inion over the vertex.



Citation by Visual evoked potentials standard

Figure A-1. Labels for points according to 10-20 electrode placement system.

A-2. Visual evoked potentials (VEPs)

Visual evoked potential (VEP) is an evoked electrophysiological potential that can be extracted, using signal averaging, from the electroencephalographic (EEG) activity recorded at the scalp. The VEP can provide important diagnostic information regarding the functional integrity of the visual pathways.

The VEP can be recorded as transient and steady-state. The transient VEP reflects cortical activity in response to a visual stimulus when the stimulus temporal frequency is sufficiently low to allow the response to each stimulus modulation to settle down to baseline before the next modulation. In contrast, steady-state VEP is elicited by stimuli at a higher temporal frequency such that there is summation of the response to produce an approximately sinusoidal VEP waveform with approximately contrast amplitude and periodicity. Consequently, the morphology of the transient VEP is more complex than that of the steady-state VEP. But when recording VEPs in response to chromatic stimuli, low temporal frequencies are commonly used to allow the response to be dominated by the parvocellular system which is tuned to low temporal frequencies. Temporal frequencies ranging from 1 to 6 Hz have been used to investigate function of the chromatic visual system using the VEP. Higher temporal frequencies are avoided, to minimise the likelihood of intrusions from the magnocellular system. In this study, we use transient VEPs as a method for estimating the brain cortex's physiological responses with chromatic lights.

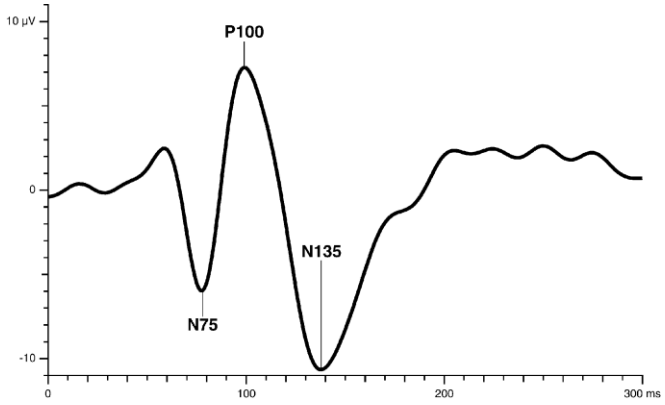
A-2.1. Transient VEPs

As the stimulus parameters, transient VEPs can be obtained as a uniform flash of light and pattern stimulation may be either presented in a reversal or onset-offset fashion.

A-2.1.1. Pattern reversal VEPs

The pattern reversal VEP has relatively low variability of waveform and peak latency both within a subject and over the normal population. Therefore, it is the preferred procedure in most circumstances. For pattern reversal, the VEP consists of N75, P100 and N135 peaks. The nomenclature consists of designating peaks as negative and positive followed by the typical mean peak latency (see Figure A-2). It is recommended to measure the amplitude of P100 from the preceding N75 peak. The peak latency of P100 shows relatively little variation between subjects, minimal within-subject

inter-ocular difference, and minimal variation with repeated measurements over time. P100 peak latency is affected by non-pathophysiologic parameters such as pattern size, pattern contrast, pattern mean luminance, refractive error, poor fixation and miosis.

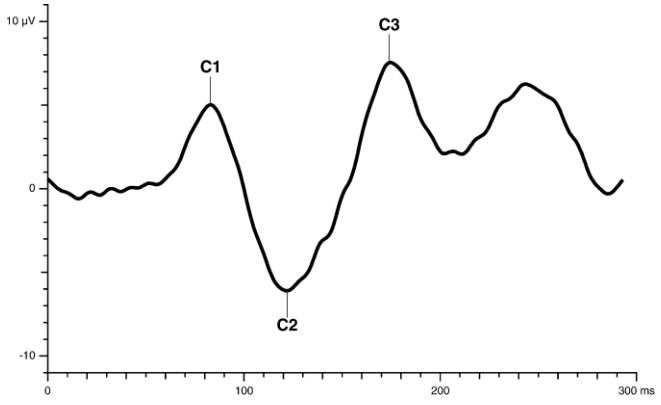


Citation by Visual evoked potentials standard

Figure A-2. A normal pattern reversal VEP.

A-2.1.2. Pattern onset /offset VEP

The onset /offset VEP is more variable in appearance than the pattern reversal VEP. The response to pattern onset /offset stimulation typically consists of three main peaks in adults; C1 (positive approximately 75 ms), C2 (negative approximately 125 ms) and C3 (positive, approximately 150 ms) (see Figure A-3). Amplitudes are measured from the preceding negative peak.



Citation by Visual evoked potentials standard

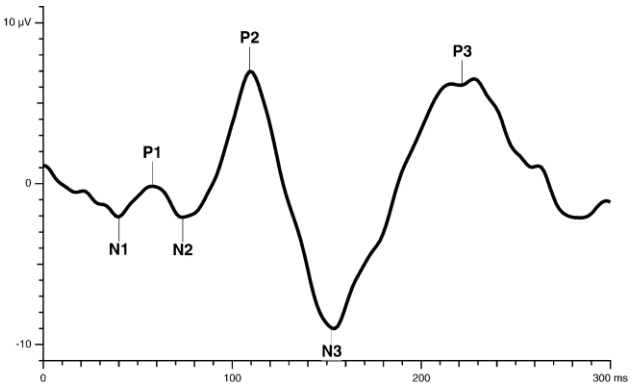
Figure A-3. A normal pattern onset/offset VEP.

A-2.1.3. Flash VEP

Flash VEPs are much more variable across subjects than pattern responses but show little inter-ocular asymmetry.

The visual evoked potential to flash stimulation consists of a series of negative and positive waves. The earliest detectable response has a peak latency of approximately 30ms post-stimulus and components are recordable with peak latencies of up to 300 ms. Peaks are designated as negative and positive in a numerical sequence (see Figure A-4). This nomenclature is recommended to automatically differentiate the flash VEP from the pattern reversal VEP. For the flash VEP, the most robust components are the N2 and P2 peaks. Measurements of P2 amplitude should be made from the positive P2 peak at around 120ms to the preceding N2 negative peak at around 90 ms.

In this study, we investigate whether the flash VEP as a proposed method can be used to locate in time and quantify the differences in cortical activity during color perception.



Citation by Visual evoked potentials standard

Figure A-4. A normal flash VEP.

A-3. EEG alpha band power ratio

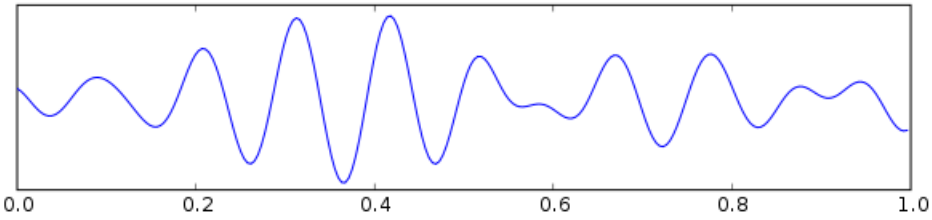
In a physiological sense, EEG power reflects the number of neurons that discharge synchronously. Because brain volume and the thickness of the cortical layer is positively correlated with intelligence, it is tempting to assume that EEG power too, is a measure that reflects the capacity or performance of cortical information processing.

There is a wide-used assessment method through comparing the ratio of alpha wave to (alpha + beta) wave to reflect the normal brain arousal level. This index suggests that comparatively ratio of alpha to beta power characterize the EEG of subjects with cognitive performance. Thus, it appears plausible to assume that during the arousal state onset alpha power decreases whereas beta power increases when cognitive activity brisk.

The calculation formula:

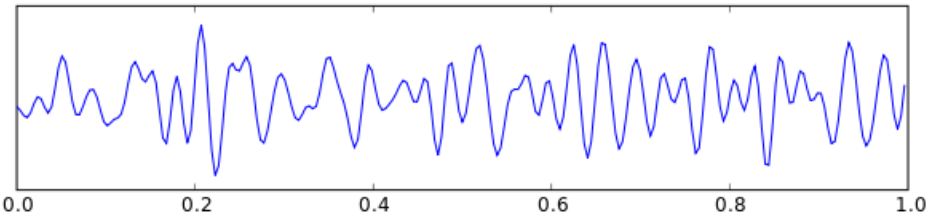
The EEG alpha band power ratio= alpha band power / (alpha + beta band power)

The alpha and beta wave of EEG sample are present below.



Cited by Wikimedia commons.

An EEG (electroencephalograph) 1 second sample. The signal is filterd to present only the alpha waves. The signal was acquired in the Oz position.



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An EEG (electroencephalograph) 1 second sample. The signal is filterd to present only the beta waves.The signal was acquired in the Oz position.

A-4. Event related potential-P300

The P300 (also known as P3 or P3b) is a large, broad, positive component in the ERP that typically peaks 300 ms or more after onset of a rare, task-relevant stimulus elicited in the process of decision making. The P300 has a centro- arietal scalp distribution that is maximal over midline scalp sites. Specifically, the P300 is thought to reflect processes involved in stimulus evaluation or categorization. It is usually elicited using the oddball paradigm, in which low-probability target items are mixed with high-probability non-target (or "standard") items. Previous studies indicated the phenomenon of P300 reflect an information processing cascade associated with attentional and memory mechanisms.

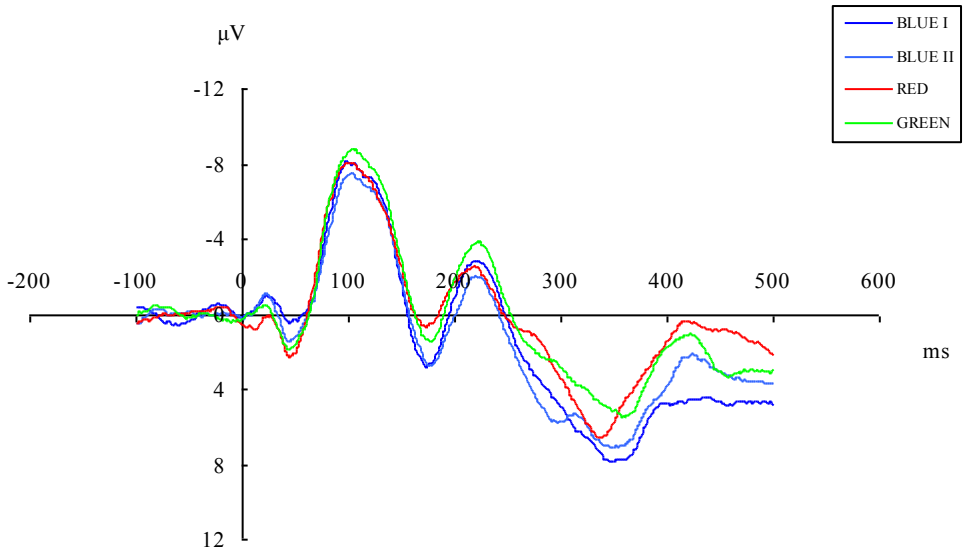
When recorded by electroencephalography (EEG), P300 surfaces as a positive deflection in voltage with latency (delay between stimulus and response) of roughly 250 to 500 ms. The signal is typically measured most strongly by the electrodes covering the parietal lobe. The presence, magnitude, topography and timing of this signal are often used as metrics of cognitive function in decision making processes. While the neural substrates of this ERP component still remain hazy, the reproducibility and ubiquity of this signal makes it a common choice for psychological tests in both the clinic and laboratory.

Oddball paradigm task: this task requires participants to detect rare randomly occurring (odd) items (e.g. a high pitch sound) in a stream of frequent items (e.g. series of low pitch sounds). It recruits attention and sensory processing (visual or auditory) (Kiehl et al., 2001; Stevens et al., 2000). In the version used in the studies reviewed here, participants were also required to count the number of odd items and report it at the end of the recording session. In that case, the task also recruits some working memory and updating functions.

In the data acquisition of P300, it is necessary to monitor the horizontal EOG and vertical EOG for eye movements and blinks. To obtain reliable measures of P300, a minimum of 36 usable trials (after artifact rejection or correction) in each stimulus category is recommended, although there is evidence that 20 trials may suffice (Cohen and Polich, 1997). Repetition of tasks can also be helpful in identifying stability of P300.

P300 is typically measured as the peak amplitude and latency within a specified latency range. Area or mean amplitude within a selected interval is another common method of quantifying P300. Both measures are derived relative to a prestimulus baseline. The scalp location where P300 is of maximum amplitude is typically used to

measure latency. If the scalp distribution of P300 is of interest, measures of amplitude should be taken at this latency for every electrode site.



Grand average P300 for each condition at C4 in the present study (N=6).

A-5. Electromyogram (EMG)

In the study of muscle physiology, neural control of excitable muscle fibers is explained on the basis of the action potential mechanism. The electrical model for the motor action potential reveals how EMG signals provide us with a quantitative, reliable, and objective means of accessing muscular information.

When an alpha motoneuron cell is activated (induced by the central nervous system or as a result of a reflex action), the conduction of this excitation travels along the motor nerve's axon and neurotransmitters are released at the motor endplates. An endplate potential is formed at the muscle fibers and innervates the motor unit (the smallest functional unit where neural control over muscular contraction occurs).

Muscle fibers are composed of muscle cells that are in constant ionic equilibrium and also ionic flux. The semi-permeable membrane of each muscle cell forms a physical barrier between intracellular (typically negatively charged compared to external surface) and extracellular fluids, over which an ionic equilibrium is maintained. These ionic equilibriums form a resting potential at the muscle fiber membrane (sarcolemma), typically -80 to -90mV (when not contracted). This potential difference in maintained by physiological processes found within the cell membrane and are called ion pumps. Ion pumps passively and actively regulate the flow of ions within the cell membrane.

When muscle fibers become innervated, the diffusion characteristics on the muscle fiber membrane are briefly modified, and Na+ flows into muscle cell membranes resulting in depolarization. Active ion pumps in the muscle cells immediately restore the ionic equilibrium through the repolarization process which lasts typically 2-3ms.

When a certain threshold level is exceeded by the influx of Na+ resulting in a depolarization of the cellular membrane, an action potential is developed and is characterized by a quick change from -80mV to +30mV. This monopolar electrical burst is restored in the repolarization phase and is followed by a hyperpolarization period.

Beginning from the motor end plates, the action potential spreads across the muscle fibers in both directions at a propagation speed of 2-6m/s. The action potential leads to a release of calcium ions in the intracellular fluid and produces a chemical response resulting in a shortening of the contractile elements of the muscle cells.

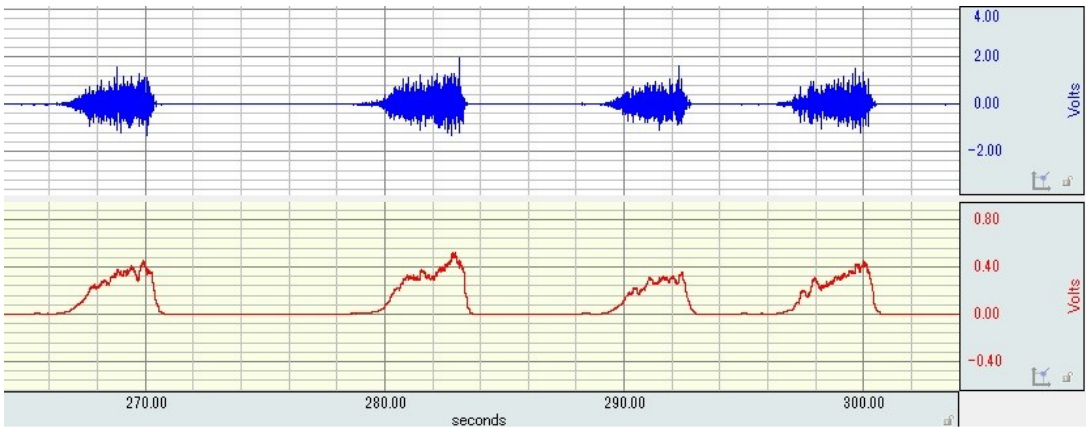
EMG signals provide us with a viewing window into the electrical signals presented by multiple muscle fibers and are in fact a superposition of multiple action potentials.

Raw EMG (red) is the unprocessed signal characterized by positive and negative peaks. The amplitudes and frequency content of this signals provides information about the

contraction or resting state of the muscle under study. It is useful when studying the activation timing of a muscle, or for verifying the quality of the signal and detecting signal artifacts.

RMS EMG (blue) is the root mean squared form of the raw signal and represents the mean power of the signal. The amplitude envelope makes it easier to view. It is useful when studying the activation timing of a muscle, and for measuring the level of activation of a muscle such as the resting level or quantifying the force generated by a muscle.

Both raw and RMS EMG signals display the electrical activities under study in the time domain.



RAW (blue) and RMS (red) EMG Signals in the present study (One subject)

Frequency Spectrum of EMG is the raw EMG that has been converted into the frequency domain by performing a Fast Fourier Transform (FFT) calculation using all available data points. The frequency spectrum reveals the frequency content of the electrical firings within the muscle. It is commonly accepted that the relevant SEMG frequencies range is between 20 - 500Hz. Looking at the frequency spectrum can also provide information not readily available in the time domain such as muscle fatigue. As muscle fatigues, the frequency of the firing decreases but the mean amplitude may remain the same. Therefore looking for indications of muscle fatigue in the time domain is not so easy. Two important measures of muscle fatigue are the median frequency (shown below with the green bar) and the mean frequency (red bar). As muscles fatigue, both mean and median frequencies decreases. However, these indicators are relevant only for isometric contractions (sustained contraction with no movement). Furthermore, by looking at the individual frequencies, it is also possible to separate the activity of the slow-twitch fibers (20 – 90Hz) from the fast-twitch fibers (90 - 500Hz).

A-6. Consent form for study participation

説明書

千葉大学工学部デザイン工学科人間生活工学教育研究分野
説明日：平成＿＿年＿＿月＿＿日
説明者：＿＿黄晶石＿＿

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・不利益；
電極の装着など、実験実施に関する煩わしさがあます。また、所定のお時間を割いて頂きます。

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同意書

実施責任者：勝浦　哲夫　　殿

実施担当者：　黄　晶石　　殿

研究課題名：XXXXXXXXXXXXXXXXXXXXXXXXXXXX

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□研究協力の手当
□個人情報の保護
□研究結果の公表
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A-7. Visual analogue scales (VAS) questionnaires

A visual analogue scale (VAS) is a psychometric response scale which can be used in questionnaires. It is a measurement instrument for subjective characteristics or attitudes that cannot be directly measured. When responding to a VAS item, respondents specify their level of agreement to a statement by indicating a position along a continuous line between two end-points. This continuous aspect of the scale differentiates it from discrete scales such as the Likert scale. There is evidence showing that visual analogue scales have superior metrical characteristics than discrete scales, thus a wider range of statistical methods can be applied to the measurements. (Reips, 2008)

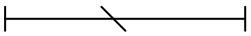
Operationally a VAS is usually a horizontal line, 100 mm in length, anchored by word descriptors at each end, as illustrated in Fig. 1. The subject marks on the line the point that they feel represents their perception of their current state. The VAS score is determined by measuring in millimetres from the left hand end of the line to the point that the subject marks.

How do you feel this product when you see it first time? Place a vertical mark on the line below to indicate how you feel your experience is now.

Bad ⌊_____⌋ Good

The VAS questionnaires in this study:

主観評価用紙　　氏名（　　）　DATE（　　）

- 以下の項目を自分の状態に合わせて線を引いて評価してください。例 

覚醒水準（眠い/すっきりする）

眠い ——— すっきりしている

集中力（集中しにくい/集中しやすい）

集中しにくい ——— 集中しやすい

提示している光の眩しさ（眩しい/眩しくない）

眩しい ——— 眩しくない

目の疲労（高い/低い）

高い ——— 低い

精神ストレス（高い/低い）

高い ——— 低い

筋の疲れ（重い/軽い）

重い ——— 軽い

筋力の発揮（出しにくい/出しやすい）

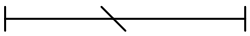
出しにくい ——— 出しやすい

- 最後に全体的にあなたが感じた疲労程度を評価してください。

全体的疲労程度（高い/低い）

高い ——— 低い

主観評価用紙　　氏名（　　）　DATE（　　）

- 以下の項目を自分の状態に合わせて線を引いて評価してください。例 

一回目

努力程度（低い/高い）

低い ——————————————————— 高い

二回目

努力程度（低い/高い）

低い ——————————————————— 高い

三回目

努力程度（低い/高い）

低い ——————————————————— 高い

Reference:

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Stevens, A.A. et al. (2000). 'Event-related fMRI of auditory and visual oddball tasks.' *Magn. Reson. Imaging* 18: 495–502.