Effects of monochromatic light on muscle fatigue and its recovery

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Abstract

The present research was designed to examine whether monochromatic light exposure influences muscle strength output and muscle recovery after fatigue. Six male subjects performed a muscle fatigue task involving maximum voluntary abduction of the first dorsal interosseous (FDI) muscle in three sessions with 40 repetitions and test contractions of the FDI muscle with 8 repetitions during 30 min to assess recovery progress. Subjects also reported their general arousal level and mood state. There were four monochromatic light conditions in the present study, and we standardized measurement units of the light power as illuminance (red, green and blue I) and irradiance (red and blue II). We found that the root mean square (RMS) of the electromyogram (EMG) of FDI was significantly decreased during the muscle fatigue task, and it then increased during recovery. However, no significant difference was found among the four light conditions. The median frequency (MDF) of the EMG signal decreased significantly under the red light condition compared to that under the blue II light condition from the 15 min after completion of the muscle fatigue task to the end of recovery. Furthermore, the alpha wave band power ratio of the electroencephalogram (EEG) was found to be significantly increased during recovery under the red light condition. These results indicate that the short wavelength light (blue) may facilitate the recovery from muscle fatigue better than does the long wavelength light (red), and the long wavelength light decreases the arousal level of the cerebral cortex after a high-intensity muscle activity. The present study proposes a novel view of the research into monochromatic light effects on muscle activities.

Keywords: monochromatic light, muscle fatigue, recovery, FDI, MDF, EEG, P300

1. Introduction

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 changes 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., 2009), motor cortex excitability (Langguth et al., 2009) and muscular strength (Crane et al., 2008) have been reported.

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 fatigue 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 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 fatigue and muscle recovery periods. Finally, we also attempted to find a connection between muscle performances and brain activity.

2. Methods

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.

2.2. Measurements

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 1. The illuminance and irradiance of the four light conditions are shown in Table 1. Before the experiment, fluorescent lamps (5700 K) in a climatic chamber (25°C, 50% relative humidity) were turned on to stabilize the illuminance (312 lx).

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 3. 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 afterward. During the experiment, we examined each subject’s EEG, P300 and EMG results. The experimental protocol is shown in Figure 2. The four light conditions (red, green, blue I and blue II) of the experiment...
Effects of monochromatic light on muscle fatigue and its recovery 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.

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.

2.2.3. Recordings

The right hand was positioned in an apparatus where the wrist and fingers, except the index finger, were constrained (Figure 3). 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 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 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.

2.3. Data analysis

Time interval in fatigue task: The subjective time interval between trials assessed the willingness of explosive muscle strength in sessions 1, 2 and 3 of the fatigue task. The mean values were calculated for every session of forty contractions trials.

%MVE: The maximal voluntary electrical activity (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).

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.

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).

P300:

The P300 ERP was elicited by an auditory “oddball” paradigm (1000-Hz standard sound-80% and 2000-Hz target sound-20%, 65 dB SPL auditory stimuli by an earphone). The tones were presented in a random series once every 2 or 3 s. ERPs were obtained in separate conditions from the EEG, and the subject indicated the occurrence of a target stimulus by pressing a button. The largest positive-going peak occurring between 250 and 400 ms was designated as the P300 component. P300 amplitude (μV) and latency (ms) were assessed by measuring component height relative to the pre-stimulus baseline and the time of peak amplitude from stimulus onset.

2.4. Statistical analysis

An analysis of variance (ANOVA) was computed for each dependent variable. We divided all light conditions into three color groups. A red, green and blue I light conditions group which were classified as illuminance; a red and blue II light conditions group which were classified in irradiance; a blue I and blue II light conditions group which were from the same light source, however, half power down in blue II light conditions. A two-way repeated measure ANOVA (color×time) was used in time interval values and %MVE analysis, a two-way repeated measure ANOVA (color×order 2) was used in EEG and P300 analysis, a one-way repeated measure ANOVA, and a pair-t test were used in MDF and subjective assessments analysis.

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 2). 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.

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.

Behavioral performance data

Time interval in the fatigue 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 (p=0.075).

**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 tended to be significantly larger than time period 2 (p=0.053), and likewise was larger than time period 3 (p=0.032). Figure 5 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 6).

**MDF in the recovery period:** Typical sets of EMG data recordings obtained before and after fatigue, together with the corresponding power spectra, are shown in Figure 7. As can readily be seen, the MDF of the EMG signal decreased progressively as a function of time. In the red, blue II group, we found the values of MDF came to be significantly larger after 15 min

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**Figure 4.** Mean time interval of three sessions during the fatigue task performance. 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).

**Figure 5.** 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 6.** 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 7.** 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.
under the blue II condition compared to the red light condition (Figure 8).

**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 9).

**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 10).

4. Discussion

The purpose of the present study was to investigate the effect of monochromatic lights on muscle fatigue and recovery. Motor performance was assessed during a time interval of explosive muscle strength in a fatigue 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 willingness of subjective muscle strength output tended to be higher under brighter light conditions (Figure 4). 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 5). However, no

![Figure 8](image)

**Figure 8.** 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)

![Figure 9](image)

**Figure 9.** (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)

![Figure 10](image)

**Figure 10.** 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)
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 6). These results indicated that after one hour of light exposure, little significant difference in muscle performance was found based 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 8). 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 9, 10). 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 intrinsically photosensitive retinal ganglion cells (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). It has been reported that short-wavelength light has more impact on subjective and objective alertness as well as melatonin suppression (Cajochen et al., 2005). 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 power as an influence factor is likewise important. It has been reported that one hundred lx of light is sufficient to increase subjective alertness (Cajochen et al., 2000). 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). Thus, the light intensity may be important in influencing the will of subjects. Furthermore, we found the low-intensity light condition (blue II) was more effective on the brain arousal level and on the muscle recovery than the high-intensity light condition. 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.

5. Conclusion

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.

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. Further studies with other comparison conditions (e.g., narrow bandwidth blue, green and red lights of equal photon density compared to broad spectrum white light) are necessary 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. The experimental method designed in this study as we know is more rigorous than any other previous studies, and through the different light intensity standard, the results of this study suggested that the muscular strength had no significant association with light color which supported by several previous studies (Profusek and Rainey, 1987; Elliot and Maier, 2007 etc.). However, the changes of light intensity could affect the subjective activeness even under the dim light conditions. The results indicated the importance of light intensity conditions.

Further research is necessary to directly document the neural pathways through which blue light exerts its influence on motor output. By studying the relationship between human physiology and light, research in photobiology will advance to the point where some attempts to foresee what the lighting practice will be and need in the future.

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