Effects of Color Temperature of Fluorescent Lamps on Body Temperature Regulation in a Moderately Cold Environment

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Abstract A study on the effects of different color temperatures of fluorescent lamps on skin and rectal temperatures in a moderately cold environment involving (i) changes in skin temperature of 7 male subjects exposed to an ambient temperature ranging from 28°C to 18°C (experiment I) and (ii) changes in skin and rectal temperatures and metabolic heat production of 11 male subjects exposed to ambient temperature of 15°C for 90 min (Experiment II) was conducted. In Experiment I, the reduction of mean skin temperature from the control value was significantly greater under 3000 K than under 5000 K or 7500 K lighting. In Experiment II, the reductions in mean skin temperature and rectal temperature were respectively greater and smaller under 3000 K than those under 5000 K or 7500 K lighting. However, metabolic heat production was not affected by color temperature conditions. The relationships between morphological and physiological parameters revealed that no significant relation of rectal temperature to body surface area per unit body weight was found only under 3000 K. Furthermore, while the mean skin temperature was independent on the mean skinfold thickness under 3000 K, a significant negative correlation between the rectal and mean skin temperatures was observed. Therefore, body heat loss might be suppressed effectively by increasing the vasoconstrictor tone under a color temperature of 3000 K, and the body shell was dependent only on morphological factors under 5000 K and 7500 K lighting. J Physiol Anthropol, 19 (3): 125-134, 2000. http://www.jstage.jst.go.jp/en/

Keywords: color temperature, fluorescent lamp, body temperature, body heat loss, cold environment

Introduction

Does the quality of lights such as color temperature affect our body temperature under similar ambient temperature and heat radiation from the same lighting source? It is known from experience that a lower or higher color temperature can make us feel warmer or cooler, and that an interior atmosphere can be influenced by color temperatures (Kruithof, 1941; Davis and Ginthner, 1990). Ishikawa (1993) has reported that thermal preference varies from 1 to 1.5°C when using a low color temperature in winter or a high color temperature in summer. These findings implied that a low color temperature is effective in a cold environment. However, evidence demonstrating the significant physiological changes to variations in body temperatures has been lacking.

The hypothesis that the color temperature of lights might affect body temperature in a moderately cold environment has been derived from our previous studies (Sako et al., 1993; Yasukouchi and Sako, 1994). In a follow-up study (Sako et al., 1993), a significant change in skin temperature is found under a moderately cold environment when the subject is directed to look at light sources that emit different color temperatures. This study reveals that the skin temperature decreases significantly under 3000 K compared with 5000 K or 7500 K lighting. In other words, the amount of heat loss from the body might be affected by color temperatures under a moderately cold environment. In an experiment in which subjects are not allowed to look at the light source (fluorescent lamp) in a moderately cold environment shows that the decrease in rectal temperature is significantly affected by the color temperature condition (Yasukouchi and Sako, 1994). Because heat radiation is constant in each color temperature condition, the color temperature could have affected the autonomic nervous system (relevant to body temperature regulation). This is the first report that demonstrates the color temperature/body temperature relationship.

In our present study, we examined: (i) the effects of color temperature of lights on cutaneous vascular responses to thermal stimuli (Experiment I), and (ii) effects of color temperatures on body temperature regulation in a moderately cold environment (Experiment II).

In Japan, there are many kinds of fluorescent lamps on the market. The range of color temperature commonly varies from 3000 to 7500 K. However, the "daylight" lamp (6500 K) developed before World War II has been extensively popular in Japan because it appears more luminous compared with incandescent bulbs which emit
lower color temperatures at the same electric power; the daylight lamp thus results in energy savings. Therefore, fluorescent lamps exceeding 5000 K are preferred not only in offices but also at home. The findings obtained in this study may contribute to selection of color temperature for lights used in a moderately cold environment, such as an excessively air-conditioned room.

Methods

This study consisted of two experiments; Experiment I investigated the effects of color temperatures of light on the skin temperature of humans subjected to an ambient thermal stimulus ranging from 28°C to 18°C, and Experiment II examined the effects of color temperatures on body temperature regulation in human subjects during prolonged exposure to a moderately cold environment (15°C). Informed written consent was obtained from each subject in Experiment I and II before participation in the study. This study had received the approval of the Ethics Committee of Kyushu Institute of Design in accordance with the recommendations regarding the use of human subjects.

Experiment I

Seven young male adults (age range: 21–24 yr) in good physical condition and free from diseases affecting the autonomic nervous function volunteered for the experiment. They were instructed to refrain from smoking, drinking and eating for at least 3 hr before the experiment. The subjects were also instructed not to look at the light source.

Color temperatures with lighting of 3000, 5000 and 7500 K (Hitachi, Ltd.) at a horizontal illuminance level of 500 lx were adjusted at the eye level. Lighting was furnished by 12 fluorescent lamps attached to the ceiling arranged in 2 rows of 3 twin fittings. Color temperature conditions were prepared by selecting the light source from three different three-band-type fluorescent lamps prior to the experiment. The general color rendering index of all fluorescent lamps was Ra 88. The physical characteristics of fluorescent lamps are listed in Table 1.

The subjects wore thin sleeveless shirts and shorts and thermistors (Sensor Technica ST-23S) were installed at various sites for measurement of skin temperatures at the forehead, upper arm, hand, abdomen, thigh, lower leg and foot, accordingly. Each subject entered a climatic chamber and rested in a semi-recumbent position on a bed with eyes closed. The ambient temperature was controlled at a thermally neutral condition of 28°C with 50% relative humidity (RH) at a given color temperature.

The subjects were allowed to open their eyes 25 min after exposure to neutral conditions before decreasing the ambient temperature linearly from 28°C to 18°C for the subsequent 30 min. The ambient temperature of 18°C was maintained for a further 10 min before terminating experiment I (Fig. 1).

Measurements were limited only to skin temperatures which were recorded (Takara K923) every minute from 25 min after exposure of 28°C to the end of experiment. The mean skin temperature was calculated from the equation of Hardy and Du Bois (1938).

Experiment II

Eleven healthy young male adults (age range: 19–26 yr), including 2 who participated in Experiment I, volunteered as subjects of Experiment II. Skinfold thickness was measured at the chest, triceps, subcapular, abdomen, suprailliac and thigh sites. The mean skinfold thickness was calculated by the equation of Hori et al. (1974). The body surface area was estimated from body height and body weight (Fujimoto et al., 1968). The physical characteristics of subjects are shown in Table 2. Instructions given to the subjects and outfits were similar

Table 1 Physical characteristics of fluorescent lamps

<table>
<thead>
<tr>
<th>Described color temperature</th>
<th>lamp</th>
<th>Ra</th>
<th>x-axis</th>
<th>y-axis</th>
<th>Actual color temperature*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000 K</td>
<td>FLR40S-EX-L/M-K</td>
<td>88</td>
<td>0.438</td>
<td>0.404</td>
<td>3100 K</td>
</tr>
<tr>
<td>5000 K</td>
<td>FLR40S-EX-N/M-G</td>
<td>88</td>
<td>0.344</td>
<td>0.358</td>
<td>5200 K</td>
</tr>
<tr>
<td>7500 K</td>
<td>FLR40S-EX75/M-G</td>
<td>88</td>
<td>0.369</td>
<td>0.322</td>
<td>7150 K</td>
</tr>
</tbody>
</table>

*Correct expression is actual correlated color temperature.

Fig. 1 Time schedule of Experiment I. Subjects close their eyes for 25 min before exposure to changes in ambient temperature after an initial 5 min acclimatization to the environment.
to those in Experiment I.

The experiment was performed in summer (August to early September). Conditions in the climatic chamber were regulated at 15°C with 50% RH. The same lamps were employed as those designated in Experiment I.

Thermistors of rectal (Sensor Technica ST-25S) and skin temperatures were installed with the subjects resting in a semi-recumbent position on a bed for 30 min under thermally neutral conditions (28°C, RH50%) in a climatic chamber (control room). The color temperature in this chamber was 4500 K.

After exposure to a thermally neutral condition, subjects entered another climatic chamber and were exposed to a given color temperature at an ambient temperature of 15°C (RH50%) for 90 min in a position similar to that in the control room. The order of exposure to the three different color temperature conditions was randomized and the experiment was performed once a day on each subject.

Rectal and skin temperatures were recorded for the last 5 min and expired gas was collected in a Douglas bag for the last 2 min before terminating exposure to the thermally neutral conditions. These values were taken as controls.

Expired gas was sampled at 2-min intervals; from 28, 58 and 88 min after exposure, and the rectal and skin temperatures were recorded every 1 min during exposure to 15°C environment. Skin temperatures were measured at seven sites similar to those described in Experiment I, and the mean value was calculated (Hardy and Du Bois, 1938). Oxygen intake and carbon dioxide production were obtained from the ventilatory volume, oxygen and carbon dioxide concentrations in the expired gas monitored spontaneously by a wet gas meter (Shinagawa Seisakusho WT-10A) and a polarographic and infrared analyzer (Fukuda Denshi RE 3000), respectively. The Weir's method (Weir, 1949) was applied to calculate metabolic heat production from oxygen intake and carbon dioxide production.

In order to evaluate the effects of color temperature on rectal and skin temperatures, three-way analysis of variance (ANOVA)—color temperature, exposure time and subject being used as sources of variation—was employed to verify data obtained in Experiments I and II. The changes in rectal and skin temperatures (vs control values) were obtained by subtracting experimental values from those measured under thermally neutral conditions (controls).

Results

Experiment I

Fig. 2 illustrates the averages and standard errors in the reduction of mean skin temperature (Δ Tms) under the three color temperature conditions. Under exposure to thermal stimulus, data (Fig. 2) were taken while the ambient temperature decreased linearly from 28°C to 18°C for 30 min with the environment kept at 18°C for the next 10 min. The results of ANOVA indicated that Δ Tms was affected significantly by the exposure time (F=1468.85, p<0.01), and significant interaction effect between color temperature and exposure time was observed (F=2.92, p<0.01). The effect of exposure time was taken as the change in ambient temperature with time. The interaction effect between color temperature and time implied that the degree of Δ Tms caused by changing thermal stimulus was different among the various color temperature conditions. Furthermore, Δ Tms was significantly greater under 3000
K than under 5000 K or 7500 K (Fig. 2).

Among the important body sites for the body heat loss, Ts of hand under 3000 K was significantly decreased with time than under other color temperatures. Although Ts of the lower leg was not affected significantly, a more decreasing tendency was also indicated under 3000 K.

**Experiment II**

On analysis with ANOVA, significant effects of color temperature on mean skin temperatures during 90-min exposure to 15°C were not observed. However, ΔTms was significantly affected by color temperatures (F=19.19, p<0.01), showing that the greatest decline of ΔTms was registered under 3000 K (Fig. 3).

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**Fig. 3** Changes in reductions of mean (ΔTms), lower leg (ΔTls) and hand skin temperatures (ΔThs) with exposure time under three color temperature conditions in Experiment II.
Significant color temperature effects were observed on skin temperature at several sites; a higher Ts measured at the forehead ($P=69.13, p<0.01$) and lower Ts values at the lower leg and hand ($P=37.49, F=64.51, p<0.01$, respectively) were demonstrated under lighting of 3000 K compared with 5000 K or 7500 K (Fig. 3).

The change in reduction of rectal temperature ($\Delta$Tr) with exposure time (Fig. 4) revealed significant color temperature effects (Fig. 4, $F=36.82, p<0.01$) as well as on rectal temperature (Tr) ($F=5.61, p<0.01$), indicating that $\Delta$Tr under 3000 K was kept at a relatively high level during the latter half of exposure to a moderately cold environment.

The averaged metabolic heat production measured at 58 and 88 min post-exposure was not affected by color temperatures (Fig. 5, $F=2.52, NS$).

**Discussion**

Generally, dominant wavelengths of light toward the red region of the visual spectrum produce a warm sensation, while those tend to blue are related to cool sensation. Earlier studies have examined this so-called "hue-heat" hypothesis using highly saturated colored surfaces or lights (Morgensen and English, 1926; Houghton et al., 1940; Berry, 1961). In 1941, Kruithof reported a feeling of comfort affected by color temperature and illuminance of lights and suggested that the use of cool light sources at low illuminance resulted in a dim or cold appearance, while warm sources at high illuminances produced unnatural color appearances. Ishikawa (1993) has reported that electrical energy used for heating/cooling systems in winter/summer seasons could be reduced by about 5 to 8% if a change in thermal sensation occurred under "daylight" or "warm white" fluorescent lamps. However, numerous studies on color temperature and illuminance have been concerned only with visual effects and psychological aspects of humans.

Since 1990, we have been conducting intensive studies on the physiological effects of color temperature of lighting, especially with aspects on the central nervous system (Deguchi and Sato, 1992; Inoue and Yasukouchi, 1992) and autonomic nervous system (Mukae and Sato, 1992; Sako et al., 1995). Regarding the latter, it was suggested that color temperature influenced the blood pressure (Sako et al., 1995) and activities of the cardiac sympathetic and parasympathetic nerves when evaluated by power spectrum analysis of heart rate variability (Mukae and Sato, 1992).

These studies demonstrated that higher color temperature enhanced sympathetic nerve activities which were observed by heart rate variability and in diastolic blood pressure in thermal neutral condition (Mukae and Sato, 1992; Kobayashi and Sato, 1992). However, Sako (1993) has found a significant decrease in mean skin
Temperature and a marked increase in diastolic pressure under a color temperature of 3000 K when compared with 5000 K and 7500 K in an ambient temperature of 15°C but not found in 25°C and 35°C. The subjects in the experiment, however, were allowed to look at the light source directly. This study prompted us to examine if color temperature of lights affected the amount of heat loss from the body exposed to moderately cold environments when subjects were not allowed to look at the light source. Yasukouchi and Sako (1994) performed an experiment in which subjects were exposed to an ambient temperature of 15°C under color temperatures of 3000, 5000 and 7500 K for 90 min in a semi-recumbent position without looking at the light source. The results showed that the decrease in rectal temperature was significantly smaller under 3000 K than 5000 K or 7500 K although we failed to observe a significant change in mean skin temperature. However, it was the first study that demonstrated objectively the effect of color temperature on body temperature.

In our present study, in order to examine if skin temperature was affected by color temperature, measurement in Experiment I was limited only to skin temperature to minimize physical and psychological disturbances to subjects by excessive routine. The findings showed that the mean skin temperature was lowered significantly under 3000 K lighting.

Results in experiment II showed that the reduction in mean skin temperature and rectal temperature from the control values were significantly greater and lower, respectively, under 3000 K than 5000 or 7500 K in a moderately cold environment of 15°C. This implied that suppression of body heat loss by subcutaneous vasoconstrictions was reflected in a minor change in rectal temperature under the color temperature of 3000 K.

Body temperature is controlled by a balance between heat loss and heat production. Body heat loss is regulated by constriction of skin venous blood flow in cold environments, and heat production is increased when the body temperature cannot cope at this stage. It is well known that body heat regulation is greatly affected by morphological characteristics such as skinfold thickness and body surface area, which are related to body insulation and heat loss area, respectively (Buskirk et al., 1963; Kollias et al., 1974).

In our previous study (Yasukouchi et al., 1988), the responsiveness of metabolic heat production to cold stimulations declines under an ambient temperature of 15°C in summer when compared with data obtained in winter. Therefore, regulation of heat loss was more important under a moderately cold environment in summer (present study) and regulation of skin blood flow as well as morphological characteristics played an important role in body temperature regulation.

In this study, there was no significant correlation between metabolic heat production and rectal temperature measured at the terminal exposure to 15°C under any color temperature (3000 K; r=0.37, 5000 K; r=0.51, 7500 K; r=0.21), confirming our previous findings (Yasukouchi et al., 1983).

In order to investigate the relationships between morphological and physiological parameters, rectal and mean skin temperatures of 11 subjects exposed to a cold environment were averaged for the last 5 min and symbolized as Tr90 and Tms90, respectively. These were taken as the representative values under the respective color temperature conditions. A significant positive correlation between Tr90 and skinfold thickness in each color temperature condition was established (3000 K; r=0.77, p<0.01, 5000 K; r=0.63, p<0.05, 7500 K; r=0.63, p<0.05), showing that morphological insulation was an important factor in maintaining body temperature regardless of color temperature conditions (Fig. 6).

In the relationships between Tr90 and body surface area per unit body weight, significant negative correlations were found under conditions of 5000 and 7500 K (5000 K; r=−0.67, p<0.05, 7500 K; r=−0.65, p<0.05) although this was not the case at 3000 K (Fig. 7). In other words, a change in rectal temperature was independent of body surface area in a cold environment under 3000 K. This implied that the amount of heat loss was suppressed effectively under 3000 K even in subjects who had a large body surface area for heat loss. This suggested that the physiological insulation at 3000 K was superior to that at 5000 or 7500 K.

Skin temperature is affected by morphological and physiological factors of the body shell (i.e., skinfold thickness and contractility of subcutaneous vessels). Although a significant relationship between Tms90 and mean skinfold thickness was not established at 3000 K (r=−0.33, NS), conditions at 5000 and 7500 K (r=−0.66, p<0.05, r=−0.79, p<0.01, respectively) were otherwise (Fig. 8). Insulation of the body shell was thus dependent on skinfold thickness at 5000 and 7500 K, while body insulation was dependent on not only body fatness but also subcutaneous vasoconstriction response to cold stimulus at 3000 K. This was supported by the facts that a significant negative relation between Tr90 and Tms90 was observed only at 3000 K (3000 K; r=−0.64, p<0.05, 5000 K; r=−0.01, NS, 7500 K; r=−0.33, NS) (Fig. 9), and that skin temperatures at the hand and lower leg were significantly decreased at 3000 K when compared with other color temperatures (Fig. 3). As these sites are very important areas for body heat conservation, body heat loss might be suppressed effectively by both morphological (Fig. 6) and physiological (Fig. 9) factors to maintain body temperature at a color temperature of 3000 K, while body heat loss was dependent only on morphological factors at 5000 and 7500 K.

The mechanism by which color temperature influenced the body temperature or vasoconstrictor tone
was not clarified in this study. However, it is well known that circadian rhythms including body temperature respond to light and that the secretion of hormones (such as cortisol and melatonin) is sensitive to light. This leads to a hypothesis that light stimuli might affect the activity of hypothalamus relevant to centers regulating body temperature, autonomic nervous system and hormonal secretion. Furthermore, previous studies have proved that different color temperatures of fluorescent lamps affect the rectal temperature, melatonin and cortisol secretion significantly (Morita and Tokura, 1996; Küller, 1986; Küller and Wetterberg, 1993), showing that the degree of hypothalamic activity is affected by the spectral composition of lights. Morita and Tokura (1996) pointed out that changes in melatonin secretion could be caused by a change in the activity of melatonin receptor located in the hypothalamus, which leads to changes in rectal temperature. In addition, studies in our laboratory have indicated that color temperature affects autonomic nervous tones and arousal levels such as heart rate variability, blood pressure, skin temperature, α wave attenuation coefficient and contingent negative variation (Kobayashi and Sato,
Effects of Color Temperature on Body Temperature

Fig. 8 Relationships between mean skin temperature (Tms90) and mean skinfold thickness (MSFT) under three color temperature conditions in Experiment II. Tms90 is the mean value for the last 5 min during cold exposure.

Fig. 9 Relationships between rectal temperature (Tr90) and mean skin temperature (Tms90) under three color temperature conditions in Experiment II. (Refer to Fig. 6 and 8 for details of Tr90 and Tms90).

This ability is determined by indices such as lower critical temperatures (Scholander et al., 1950ab; Ishii, 1976) and the Δ M/Δ Tms ratio (when Δ M represents the increase in metabolic heat production, Ogata, 1970). According to these indices, 3000 K lighting might induce a cold tolerance greater than lightings at 5000 and 7500 K even under similar ambient temperature conditions.

Thus, a selected color temperature lighting affected body temperature regulation in response to a cold environment; excess body heat loss was suppressed under lighting at 3000 K. Color temperature might be an important factor in body temperature regulation, especially

1992; Mukae and Sato, 1992; Sako et al., 1993; Ejima and Yasukouchi, 1997; Iwakiri and Yasukouchi, 1998). It is thus rational to conclude that different color temperatures of lights affect activities of the hypothalamus, leading to changes in vasoconstrictor tone and resulting in changes in skin and rectal temperatures in a moderately cold environment.

It has been established that having a greater ability to restrain heat loss from the body surface is advantageous to body temperature regulation in a cold environment from the standpoint of cold tolerance and energy conservation.
in summer when the response of enhanced metabolic heat production to a cold environment becomes “blunted” (Yasukouchi et al., 1983).

Recently, a study on the indirect effects of lighting has revealed that the color temperature of light sources should be selected according to psychological and physiological parameters such as the arousal level and autonomic nervous system to best harmonize season-attenuated functions in equilibrating homeostasis in humans to optimally respond against sudden changes in the environment. Further studies, especially on the physiological aspects relevant to indirect effects, or non-visual effects, are warranted.

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