Physiological Effects of Sudden Change in Illuminance during Dark-Adapted State

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Abstract. To derive an optimal illuminance of nighttime illumination, we conducted an experiment with 7 healthy young individuals and 7 healthy elderly individuals as subjects. After 20 minutes of adaptation to darkness, subjects were exposed to illumination under 5 conditions comprising 0.5 lx, 1 lx, 3 lx, 10 lx, or 30 lx vertical illuminance of the facial region, and heart rate variability (HRV) and electroencephalogram (EEG) were measured, and discomfort was evaluated by subjective report. Results of LF/(LF + HF) (LF = low frequency, HF = high frequency) demonstrated a V-shaped trend for the young groups beginning during exposure and ending post exposure, with 3 lx conditions representing the minimum value, a value markedly lower than that for 30 lx conditions. From these results we inferred that approximately 3 lx illuminance could best suppress physiological stress. Evaluation of discomfort by subjective report also demonstrated an increase in discomfort evaluation scores under high illuminance conditions. The a-wave proportion of EEG during exposure fell markedly on 3 lx or higher illuminance conditions, and we inferred that visual sensory information and cortical activity level were adequately attained in 3 lx or higher illuminance conditions. These results suggest that the optimal illuminance of nighttime illumination is approximately 3 lx.

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Introduction

Since Edison's 1879 success in illuminating a light bulb with the use of a carbon filament produced by carbonizing a cotton thread, artificial illumination has developed rapidly in the roughly 120-year interval, and humanity has obtained a second light source to substitute for the sun. Various and diverse light sources and illumination equipment have

been developed, and in present-day society, activities such as reading and other fine visual work proceed even at night with no difference at all from day, and our lifestyles are thus endowed with great freedom. In some cases, however, the negative effects of bright nights on people, plants, and other organisms represent a problem, leading in recent years even to the coining of the term "light pollution". One particular problem in terms of its effect on humans is nighttime illumination.

The human eye is equipped with extraordinary sensitivity adjustment functions including pupil diameter adjustment, cone and rod changeover, and adjustment of visual pigment, and the eye can accommodate conditions as dim as a roughly 0.3 lx moonlight night or as bright as a roughly 100,000 lx clear day. However, because some time is required for adjustment to bright or dark areas, a gradual change in brightness can be accommodated with comparatively few problems, while cases of sudden, major change engender various problems. A particular problem with nighttime activity lighting is a sudden increase in illuminance from a dark-adapted state. Nearly all illumination systems currently in ordinary household use provide sudden illumination at a same level as that during the pre-sleep light-adapted state, even during a dark-adapted state such as a nighttime trip to the lavatory; thus, a user experiences the discomfort of blinding light.

There is considerable research concerning illumination in the living environment and its physiological effects. Sugimoto (1980, 1981) investigated the physiological effects of illumination in illuminated environments which has illuminance from 10 lx to 2000 lx and reported a rapid increase in mean heart rate at illuminance levels higher than 320 lx–560 lx. Bernecker et al. (1994) reported that tympanic temperature rises with illuminance in illuminated environments which has illuminance from 20 lx to 3200 lx. In illuminated environments which has illuminance from 200 lx to 3125 lx, Sato et al. (1996) reported an increase in heart rate under conditions of 3125 lx compared to conditions of 500 lx and 1250 lx. Küller and Wetterberg (1993) investigated physiological effects in illuminated environments which has illuminance of 450 lx and 1700 lx

provided by two types of fluorescent lamps, daylight color and warm white color, and reported that electroencephalogram (EEG) α -waves decreased throughout the day under conditions of 1700 lx provided by a daylight color fluorescent light.

These results together suggest that high illuminance environments create a physiological burden or stress. However, most present-day homes or hotels and other lodging facilities do not typically contain lighting equipment that provides illumination levels this high even at night, the brightest room in an ordinary home being approximately 150 lx. Moreover, Mukae and Sato (1992) sought to verify these effects on the autonomic nervous function through heart rate variability (HRV), as did Kobayashi and Sato (1992) through an index of blood pressure, and in neither case were such effects confirmed, despite the setting of high illuminance conditions of 900 lx and 2000 lx. From this perspective, it is difficult to conclude that differences in illuminance in the present-day household environment have much of a physiological effect. However, all of the research previously discussed investigated effects in a thoroughly light-adapted steady state without considering the topic addressed here; namely, the effects of overpowering light due to sudden illumination during a dark-adapted state, and even apart from the work discussed, such research does not exist. Discomfort caused by overpowering light may manifest itself as an emotional reaction and cause various physiological effects, and it is entirely plausible that results could be obtained which differ from those of the preceding research discussed above.

The importance of these problems is also growing now at the outset of a dramatically aged society. Because elderly individuals make more frequent trips to the lavatory at night than young individuals, their requirements for nighttime illumination are greater; however, a questionnaire survey carried out by Nobuhara et al. (1997) found that nearly 30% of respondents went to the lavatory without turning on a light for reasons including excessive brightness. These results indicate that many elderly individuals currently face the problems discussed above and that the risks posed by their activities in the dark are growing. Given the ongoing demographic aging of society, the severity of this problem is likely to grow.

In this context, our research investigated the physiological effects accompanying a sudden change in illuminance on a dark-adapted state, conceptualized as the use of lighting during a semi-waking state at night, and an experiment and discussion were carried out with the object of deriving an optimal nighttime illuminance of illumination.

Methods

Subjects

7 healthy male college students and graduate school

students (mean age 21.6 years), and 7 male elderly individuals age 65 or older (mean age 68.0 years) participated as subjects. For all subjects a previously conducted preparatory experiment ascertained that electrocardiogram (ECG) displayed no arrhythmia patterns.

Experimental conditions

Experimental conditions comprised the 5 conditions of 0.5, 1, 3, 10, or 30 lx vertical illuminance of the facial region. The light source used was a three-band fluorescent lamp with a color temperature of 3000 K.

The experiment was conducted in a climatic chamber controlled to a temperature of 25 °C and a relative humidity of 50%. The light source consisted of two 40-watt, high frequency straight tube fluorescent lamps (color temperature 3000 K, color rendering index 88) suspended from the center of the ceiling of the experimental chamber, and light adjustment control was carried out by a personal computer (NEC PC-9801M). A reclining seat for the subject was placed in the center of the experimental chamber.

Procedure

The experimental schedule is shown in Fig. 1. After electrodes were attached, the subject entered the experimental chamber and sat in the reclining seat to begin the experiment. The experimental chamber was kept at 0 lx for 20 minutes after the start of the experiment to adapt the subject to the dark; 2 minutes of illumination was then carried out by sudden illumination at the illuminance of each experimental condition; the chamber was returned to 0 lx; and after 6 minutes the experiment ended. To measure HRV after 15 minutes from the start of the experiment until the end of the experiment, a metronome with a period of 0.33 Hz was used for respiratory control. Subjects remained seated in the reclining seat until the end of the experiment. Physiological measurements were made at 17–19 minutes after the start of the experiment (immediate pre-exposure; session 0), at 20–22 minutes (exposure; session 1), 22–24 minutes (post-exposure; session 2), and at 26–28 minutes (post-exposure; session 3); immediately after conclusion of the experiment, a subjective evaluation was also made concerning discomfort for the change in illuminance.

Time slots when the experiment was performed were 9:00–10:30, 10:30–12:00, 13:00–14:30, 14:30–16:00, and 16:00–17:30; a maximum of five times in one day. A subject was exposed to one condition in one day, and in consideration of circadian rhythm, a given subject participated in the experiment during the same time slot in each instance.

Measurements

EEG and ECG measurements were made as

Fig. 1 The time schedule of the experiment. Immediate pre-exposure; session 0. Exposure; session 1. Post-exposure; session 2, 3.

physiological indices. EEG was recorded by monopolar lead from the Cz according to the international 10/20 system, using an Ag/AgCl electrode and referenced to a left earlobe. Amplification was provided by a biological amplifier (NIHON-KODEN MEG6100) with a time constant of 0.3 sec and an upper cutoff frequency of 30 Hz. The ECG was recorded by thoracic bipolar lead and was amplified by biological amplifier as described above with a time constant of 1.0 sec and an upper cutoff frequency of 100 Hz. Both the ECG and EEG were digitized on-line at a sampling frequency of 500 Hz. Subjective evaluation of discomfort was carried out through a five-level evaluation consisting of “not uncomfortable”, “a little uncomfortable”, “uncomfortable”, “fairly uncomfortable”, and “extremely uncomfortable”.

Data analysis

Data for the EEG sampled at 500 Hz was culled to a 100 Hz equivalent, Fast Fourier Transformation (FFT) was used for frequency analysis at 1024 point (10.24 second) intervals, a mean frequency spectrum for approximately two minutes in each observation session was determined, the a-wave proportion in 8–25 Hz (a-wave power/(a-wave power + b-wave power)) was calculated, and this served as a central nervous activity index.

HRV was analyzed from the ECG data. R-wave peak detection was carried out and R-R intervals were calculated for the ECG data obtained; a frequency analysis for successive R-R interval values was performed by the Maximum Entropy Method (MEM), with a maximum model index of 10, a spectral resolution of 150, and an analysis frequency band of 0.05 Hz; and a frequency spectrum was calculated. The frequency spectrum for HRV includes two components. The first is Mayer wave sinus arrhythmia

(MWSA), a sinus arrhythmia related to Mayer waves in blood pressure presenting nearly 0.1 Hz peaks, and the other is respiratory sinus arrhythmia (RSA), a respiratory arrhythmia presenting peaks matched to respiratory frequency. The former is thought to reflect both sympathetic and parasympathetic nervous activity, and the latter is thought to reflect parasympathetic nervous activity. (Pomeranz et al. 1985) The power of the 0.05–0.15 Hz MWSA component (LF) and the 0.20–0.42 Hz RSA component (HF) was determined from the frequency spectrum obtained, $LF/(LF + HF)$ was calculated, and this was taken as a relative activity level index for sympathetic nerves in autonomic nervous activity.

In consideration of circadian rhythm, all observations for a given subject were made in the same time slot, but some discrepancies from pre-exposure control conditions were noted, indicating a possible effect from initial status. In regression analysis carried out for $LF/(LF + HF)$ data and a-wave proportion data, results with control condition data as the independent variable and exposure data for each condition as the dependent variable showed a high correlation in the a-wave proportion data, indicating that a-wave proportion is strongly affected by initial status. Thus, for the a-wave proportion of EEG, control values were adjusted to the origin, based on the regression equation obtained.

Subjective reports obtained were assigned scores of 0–5 corresponding to “not uncomfortable” through “extremely uncomfortable” in that order, with these serving as discomfort evaluation scores.

Results

Fig. 2 shows results for $LF/(LF+HF)$ in HRV. During

Fig. 2 The effect of change in illuminance on LF/(LF + HF) in HRV. Means and standard errors are shown. *: $p < 0.05$ (t-test).

Fig. 3 The effects of change in illuminance on a-wave proportion ($a/(a + b)$) of EEG. Means and standard errors are shown.

Fig. 4 The effects of change in illuminance on subjective discomfort scores (0-"not uncomfortable"; 1-"a little uncomfortable"; 2-"uncomfortable"; 3-"fairly uncomfortable"; 4-"extremely uncomfortable") Means and standard errors are shown.

illumination, both the young individuals group and the elderly individuals group displayed a valley shaped pattern centered on 3 lx conditions, and in the young individuals group this trend persisted until session 2 (the 0–2 minutes after exposure), following exposure. In the young group, t-test results showed a significant difference ($P < 0.05$) between 3 lx conditions and 30 lx conditions among session 1 and session 2.

Fig. 3 shows variations in the a-wave proportion ($a/(a+b)$) of EEG. Up to 3 lx conditions, both the young group and the elderly group displayed a pattern of decreasing a-wave proportions as illuminance increased, but under higher illumination conditions, a further reduction was not observed.

Fig. 4 shows results for discomfort evaluation by subjective report. The young group presents a tendency of increasing discomfort with increasing illuminance, but the elderly group presents no such tendency.

Discussion

In the present experiment the results for HRV in younger group showed a marked increase in LF/(LF + HF) under high illuminance conditions from light exposure until post light exposure (Fig. 2). We speculate that this is caused by the arousal of discomfort in the form of a blinding sensation accompanying the sudden change in illuminance, and from this we infer that the related emotional effects act on the autonomic nervous system to create a high state of sympathetic nervous activity. The LF/(LF + HF) values were also lowest under 3 lx conditions and showed a pattern of increase at lower illuminance conditions. This increase in LF/(LF + HF) values may reflect enhanced sympathetic nervous activity caused by feelings of unease specific to low illuminance. Sugimoto (1980, 1981) concluded from the change of mean heart rate that physiological burden is minimized at 320 lx–560 lx and increases at either lower or higher illumination, but this research also found that in a dark-adapted state, a similar V-shaped pattern emerged for areas with lower illuminance. Not only does enhanced nighttime sympathetic nervous activity caused by changes in illuminance lead to unnecessary physiological stress, it is also seemingly bad for resumption of sleep, and from the perspective of effects on the autonomic nervous system, we feel that a level of roughly 3 lx is appropriate.

However, the effects of illumination were not as strongly manifest in the elderly group as in the young group. We speculate that this may be an effect caused by an age-attended decreased functionality in autonomic nervous response to external environmental stimuli (Reardon and Malik, 1996). The results of subjective evaluation by the elderly group which show no marked increase in discomfort evaluation scores even in high illuminance conditions also indicate that an effect of decreased functionality in sensory perception or cognitive processing cannot be ruled out. In either case, the wide discrepancy in reactions among the elderly due to aging complicates efforts to determine an optimal illumination, but if we assume the appearance of a pattern similar to that among the young individuals during light exposure, adoption of roughly 3 lx as in the case of the young individuals would seem to create no problems.

EEG results showed a decrease in the α -wave proportion only during light exposure. This shows that EEG frequency components shifted from the α -wave band to the β -wave band. While this change can be ascribed to α -blocking, there are two conceivable causes. α -blocking upon eye opening due to eye closure is a phenomenon readily observable in anyone and results when visual information causes the reticular nuclei of the brainstem to effect heightened cerebral cortex activity. We conjecture that the high α -wave proportion under low illuminance

conditions of 0.3 lx and 1 lx is most likely due to a scarcity of light and an insufficient supply of visual information. Because α -waves also show a declining pattern due to discomfort (Miyake and Tanaka 1984), another possible cause is brilliant light-induced discomfort. However, several factors indicate that the former effect is larger: the absence of a marked increase in discomfort among the elderly individuals under high illumination conditions, according to subjective evaluation results; the lack of persistence in this pattern until the post light exposure period; and the stable results under illuminance conditions greater than 3 lx. Given that household accidents involving the elderly have increased in recent years, nighttime illumination is a crucial factor for ensuring visual information and a cortical level of waking, and we feel that a level of 3 lx or more is appropriate for safe nighttime activity.

HRV results, an index of autonomic nervous activity, indicate that approximately 3 lx is appropriate from the standpoint of physiological stress avoidance and resumption of sleep, while EEG results, an index of central nervous activity, indicate that 3 lx or higher is appropriate in terms of safety. In this respect, 3 lx vertical illuminance of the facial region was thus derived to be appropriate illuminance in a nighttime semi-waking state. While the current research considered optimal nighttime illuminance in terms of physiological effects during a sudden change in illuminance, the future is likely to hold requirements for considering not only nighttime illuminance levels, but also light adjustment that provide gentle starting to relieve the discomfort of overpowering brightness that comes from turning on a light. In future, we intend to consider favorable nighttime illumination that incorporates these factors.

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