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Article

Analysis of Occupants' Visual Perception to Refine Indoor Lighting Environment for Office Tasks

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Abstract: The combined effects of color temperature and illuminance in a small office on visual response and mood under various lighting conditions were examined in this study. Visual annoyance tests were conducted using a sample of 20 subjects in a full-scale mock-up test space. Computer and paper-based reading tasks were conducted for 500 lx and 750 lx illuminance levels under 3,000 K, 4,000 K and 6,500 K conditions. Two hypotheses were considered for the test in this study. The primary hypothesis was that visual perception is affected by the color temperatures of light sources. The secondary hypothesis was that better moods, such as relaxed and cozy feelings, are associated with low color temperatures given equal illuminance levels. The visual environment under the 3,000 K condition was characterized by glare and brightness, resulting in visual discomfort when target illuminance was higher than 500 lx. Occupants preferred 500 lx under the 6,500 K condition, and 500 lx and 750 lx under the 4,000 K condition, reporting better visual satisfaction when performing office tasks. Prediction models for visual comfort suggest that the less that subjects are visually bothered by light during tasks, the more visual comfort they feel. User satisfaction with light source color is critical for the prediction of visual comfort under different lighting conditions. Visual comfort was the most influential factor on mood. Lower color temperature was associated with better mood at lower illuminance levels, while higher color temperature was preferred at higher illuminance levels.

Keywords: color temperature; illuminance; visual response; reading task; office; visual comfort; mood

1. Introduction

Fluorescent light sources with well-designed shielding devices are effectively utilized for lighting in office environments, since wide areas can be covered uniformly and the resulting visual comfort is acceptable. Despite these advantages, careful attention should be paid to the application of fluorescent light sources for office lighting, since their spectral composition in the visible light region is not sufficient for good color rendering and visual comfort. In some cases, the spectra are not uniformly distributed in the visible light region and obscure the perceptions of colors and objects. These limitations influence visual performance relevant to office tasks. The uneven composition of spectra in the visible light region, as summarized by the color temperatures of light sources, influences visual sensation [1,2]. The color temperatures of light sources and illuminance levels influence human visual responses and perceptions that are critically linked to visual satisfaction and comfort [3,4].

Illuminance and color temperature are quantitative indexes used to evaluate office lighting. A variety of studies have been conducted to examine the effects of color temperature on visual perception. Visual perception and mood are affected by color temperature even if the illuminance level is constant [5–10]. Positive visual perception and mood increase efficiency when making some types of decisions and promote creative work performances [11]. Negative visual effects impaired task performances and productivity when office tasks were performed [12,13]. People showed a strong tendency to believe that visual perception and mood are influenced by lighting conditions [14]. A majority of office workers in enclosed spaces prefer better lighting conditions [15,16]. The magnitude of illuminance changes is a critical factor that influences visual comfort [17].

When illuminance is constant in an office space, visual perception may still be affected by the color temperature of light. This phenomenon directly affects visual comfort and mood in office workers. Various studies have examined the influence of lighting conditions on office workers [3,4,6–13]. Higher illuminance conditions were evaluated as more intense than lower illuminance conditions. General interpretations regarding glare perception under different illuminance conditions were provided by these studies; however, the visual environments and conditions considered in the studies did not include general office tasks such as paper- and computer-based visual tasks. These studies were also confined to analyses of mood under different lighting conditions, and lacked analyses regarding the effects of stimulating factors on visual discomfort. Accordingly, meaningful implications of visual perception in terms of visual comfort were not obtained.

Therefore, this study examine visual responses to a variety of lighting conditions including different target illuminance levels and color temperature conditions, since these two factors function as visual stimulation elements that affect visual perception. The combined effects of target illuminance level and color temperature on visual responses and mood in office spaces are analyzed in this study in order to design comfortable lighting environments for office tasks. Visual perception and annoyance tests were conducted in a full-scale mock-up space, where six office lighting conditions were set up for computer and paper-based reading tasks.

2. Research Hypothesis

Two hypotheses were considered in this study to examine visual perception and mood responses under different color temperature and illuminance conditions that are common in office environments. The primary hypothesis was that visual perception is affected by the color temperatures of light sources. It was predicted that low color temperatures that primarily consist of long wavelengths in the visible spectrum are associated with stronger visual stimuli, such as glare, brightness, and distraction, and are more likely to lead to visual discomfort, compared to the short wavelengths that represent the high color temperatures.

The secondary hypothesis was that better moods, such as relaxed and cozy feelings, are associated with low color temperatures given equal illuminance levels. It was predicted that mood would become worse as the target illuminance level increased under the same equal color temperature conditions. The perceptions of visual comfort that are affected by visual stimulation factors were also expected to significantly influence mood under different lighting conditions.

3. Research Method

3.1. Space and Lighting Conditions

Visual annoyance tests were performed in a full-scale mock-up office space, which was constructed for the evaluation of visual responses in a variety of control settings. Figure 1 illustrates the detailed layout of the mock-up space. The dimensions of the space were 4.9 m wide, 2.8 m deep and 2.65 m high. The windows were 1.5 m in height, and were glazed with double pane glass with 62% light transmittance. Venetian blinds were installed on the windows to control daylight.

The space was furnished like a small private office. The floor was covered with beige linoleum, and the walls were painted a light green color that generated no specular reflection. An array of 0.6 m by 0.6 m suspended grids covered with white acoustic panel boards was installed on the ceiling. Two wooden desks with dimensions of 1.2 m (L) × 0.45 m (W) × 0.75 m (H) were placed in the room. The desktop surfaces were light brown and generated no specular reflections, and two chairs were provided. A notebook computer with a 39.6 cm thin-film transistor (TFT) screen was installed on each desk for the office tasks. The resolution of the notebook screen was 1024 × 768 pixels.

Fluorescent lighting fixtures were placed on the ceiling at appropriate distances to meet required illuminance levels for office tasks. Figure 2 shows detailed description of the lighting fixture. The fixtures were recessed with direct distribution of light. Parabolic troffers with louvers were used for the fixtures, and the depth of each troffer was 7.5 cm. Four T8 fluorescent lamps were used for each lighting fixture. The input wattage of each lamp was 18 W. The color produced by each fixture was constant over the entire test period once power was supplied.

Overall, the lighting fixtures provided a generally uniform distribution of light. The layout of the lighting fixtures is shown in Figure 1. The target desktop illuminance levels were 500 lx and 750 lx in this study, which are considered the minimum and medium illuminance levels for the performance of medium contrast or small size visual tasks in office environments [18]. The mean desktop illuminance generated by the full light output of lighting fixtures was 950 lx. Since this illuminance level by the lighting fixtures is too high for general office tasks, a rotary dimming controller was installed to control the illuminance. Setting points of the rotary dimming controller were exactly determined in order to keep the target illuminance levels. Windows were blocked to prevent the transmission of daylight and the target illuminance was maintained by electric lights only.

Figure 1. Detailed view of full-scale mock-up model space.

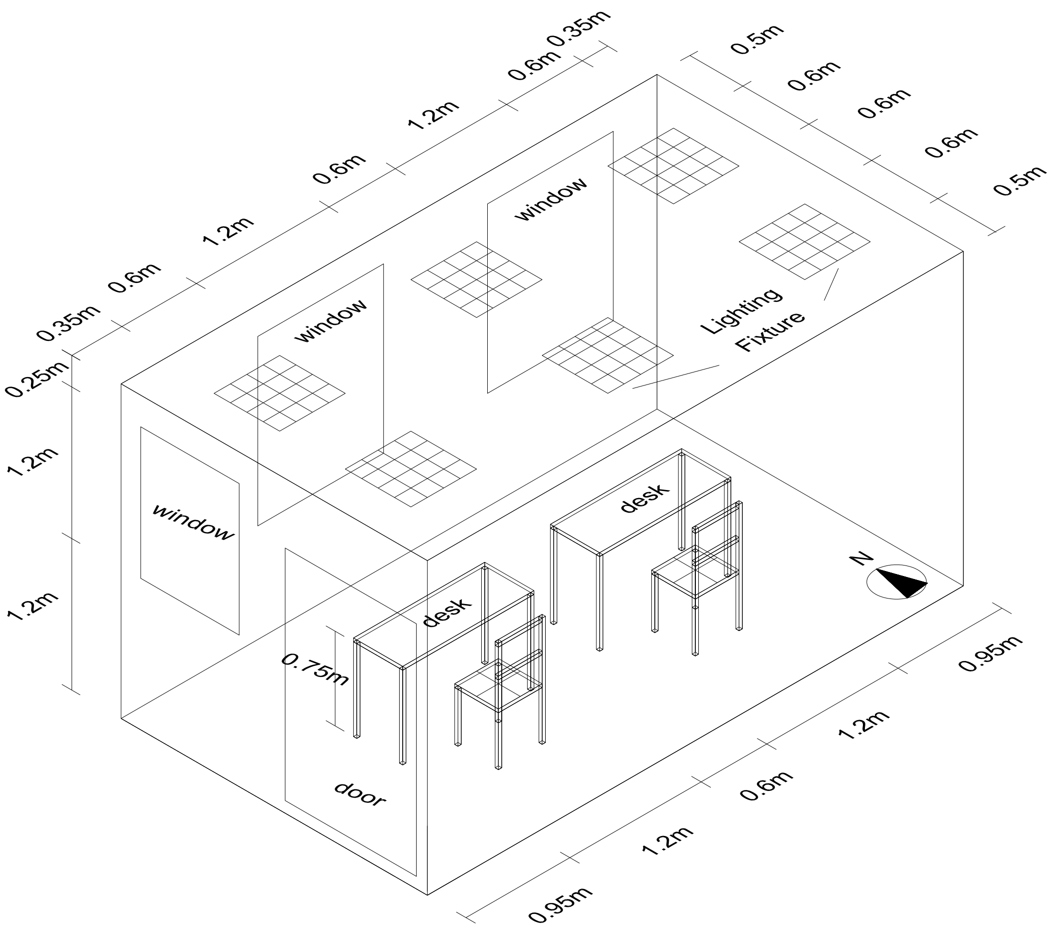
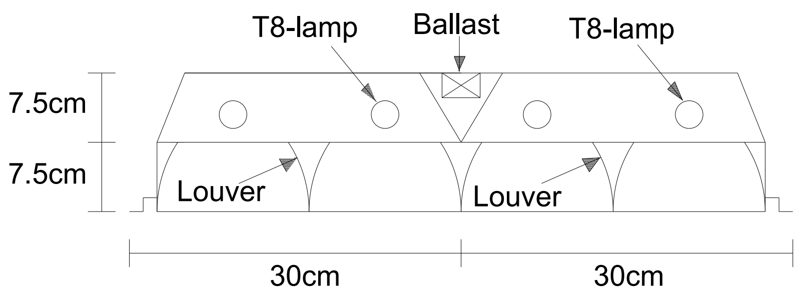


Figure 2. Section of fluorescent lighting fixture.



In order to control color temperature and illuminance levels, fluorescent lamps that had three correlated color temperatures (CCTs) were used for the fluorescent fixtures. A spectrometer was used to measure the spectral distributions and color temperatures of the fluorescent lamps. The CIE chromaticity coordinates and color temperature are summarized in Table 1. The color temperatures were 2,999 K, 3,995 K and 6,481 K according to the values on the CIE chromaticity coordinates [18]. In practice, the color temperature measurements were categorized as 3,000 K, 4,000 K, and 6,500 K for lighting design.

Table 1. Measured CIE Chromaticity coordinates and color temperature.

Properties		Fluorescent Lamp		
		A	B	C
CIE	*x*	0.4369	0.3803	0.313
Chromaticity Coordinate	*y*	0.4041	0.3754	0.3317
Color Temperature [K]		2,999	3,995	6,481

For each color temperature condition, the target illuminance levels on desktop surface were kept equally using the rotary dimming controller. The illuminance sensor positioned at the desktop detected illuminance and controlling setting was fixed when the target illuminance was met. For each condition, the light output from lamps was not measured, but the target illuminance level was used as an index for a final setting of lighting conditions.

The example of spectral distributions of the lamps is shown in Figure 3. Longer wavelengths that generate reddish colors were stronger in the spectrum of the 3,000 K lamp. For the 6,500 K lamp, the effects of reddish color became significantly weaker, but the short and medium wavelengths that generate bluish and green colors became stronger. Six different lighting conditions were generated by the combination of two illuminance levels and three color temperatures. The six cases were 500 lx with 3,000 K (Case 1), 750 lx with 3,000 K (Case 2), 500 lx with 4,000 K (Case 3), 750 lx with 4,000 K (Case 4), 500 lx with 6,500 K (Case 5), and 750 lx with 6,500 K (Case 6).

3.2. Questionnaires, Subjects, and Pre-Instruction

The questionnaires used for visual annoyance tests included three categories: general questions, questions regarding visual annoyance, and questions regarding the perceptions of visual stimulation and mood. The general questions included questions about age, gender, color blindness, and preference and sensitivity to light.

The questions used to assess visual annoyance included visual responses such as annoyance with tasks, visual satisfaction with color of light, and visual distraction. The questions used to assess the visual perceptions of stimulation factors included visual responses, such as sensation of glare, and visual stimulation. Seven questions regarding mood according to visual perception were also included. The survey questions and the voting scale used for the annoyance test are shown in Tables 2 and 3.

Twenty undergraduate students were recruited for the tests. All subjects had normal vision and were not color blind, and all were familiar with office tasks such as reading and documentation using computers and paper. Pre-instruction regarding the tests were conducted in a room adjacent to the test space before the main annoyance test began. Then, the subjects were asked to answer the general questions.

While the subjects followed instructions and answered the general questions, they had enough time to adapt their eyes to photopic vision conditions, which describe the indoor lighting environment used in this study.

Figure 3. Spectral Distribution of Fluorescent Lamp [5]. (**a**): 3,000 K; (**b**): 4,000 K; (**c**): 6,500 K. Reprinted with permission from [5].

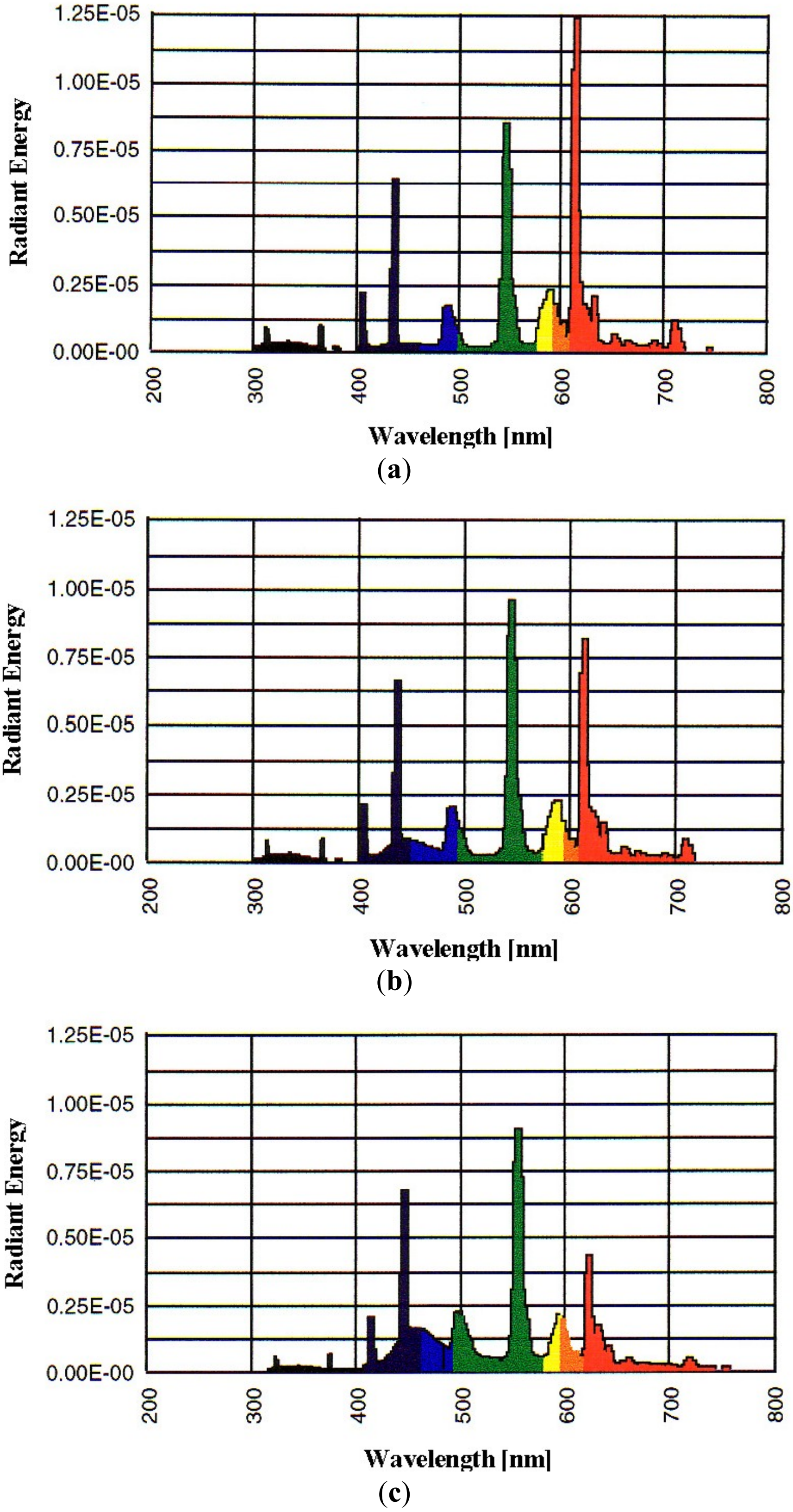


Table 2. Survey questionnaires for visual annoyance and comfort.

No.	Questionnaire content	Voting scale							Questionnaire content
		−3	−2	−1	0	1	2	3	
C1	Not satisfied with light color								Satisfied with light color
C2	Feel visual distraction								Feel no visual distraction
C3	See object visually unclearly								See object visually clearly
C4	Feel eye fatigue								Feel no eye fatigue
C5	Light does not hinder task								Light hinder reading task
C6	Visually uncomfortable								Visually comfortable

Table 3. Survey questionnaires for visual stimulation factors and mood.

No.	Questionnaire content	Voting scale							Questionnaire content
		−3	−2	−1	0	1	2	3	
VT1	Feel visual stimulation								Feel no visual stimulation
VT2	Hard to see letter clearly								Easy to see letter clearly
VT3	Feel dim for task								Feel bright for task
VT4	Feel no anxious due to light								Feel anxious due to light
VT5	Feel visually cold								Feel visually warm
VT6	Feel no glare for task								Feel glare for task
M1	Light make you dislike space								Light make you like space
M2	Light make you feel unpleasant								Light make you feel pleasant
M3	Feel no attraction to space								Feel attraction to space
M4	Feel no tense								Feel relax
M5	Feel fidgety								Feel no fidgety
M6	Feel room is not cozy								Feel room is cozy
M7	Feel room is cramped								Feel room is spacious

3.3. Task and Data Monitoring

Computer and paper-based reading tasks that are often conducted in offices were assigned to all subjects. News articles containing generally suggestive remarks were prepared in advance for the annoyance tasks. The articles were printed in paragraphs in Times New Roman 12 point font with a line spacing of 1.5 using Microsoft Word software. For the two reading tasks, subjects were asked to identify the letters 'eul' and 'reul' in the paragraphs.

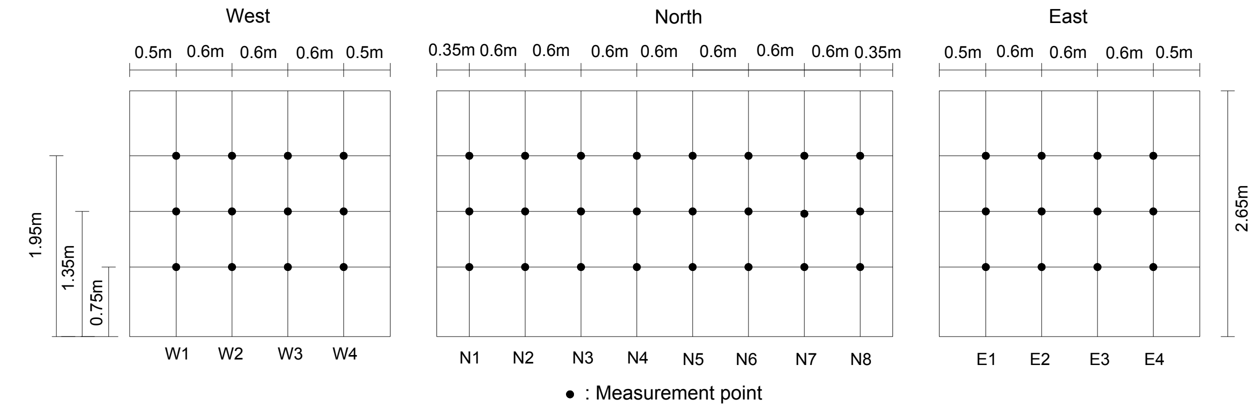
For the paper-based task, the subjects were asked to read paragraphs printed on A4-sized white paper of the type used for general documents and to mark all occurrences of the two letters on the paper. For the computer-based task, the subjects were asked to read the news articles on computer screens and to mark the letters 'eul' and 'reul' on paper.

The task given in this study identified the tasks, which were typically used in previous studies [2,19–24]. In general, proof reading and typing tasks were commonly used for the studies. In some cases, a document holder was used to minimize unnecessary eye movements during tests.

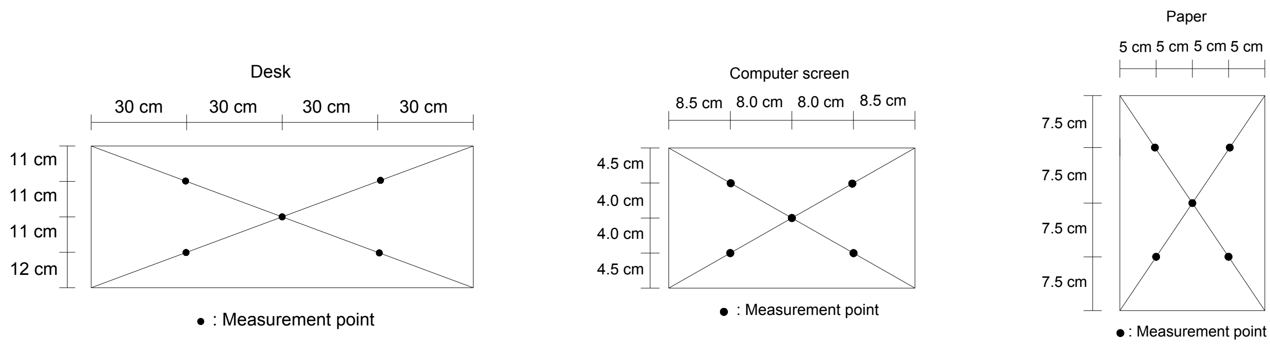
Visual annoyance tests were conducted under the six lighting conditions described in Section 3.1 and lasted for 40 min. The tests were conducted in the evening, when no daylight was transmitted through the windows into the test space. At the end of the annoyance test, all subjects were asked to answer the survey questionnaires summarized in Tables 2 and 3. A voting scale with seven categories was utilized to rate questionnaire answers.

The illuminance levels and luminous on desktop and wall surfaces were measured. The measurement points of illuminance and luminous on walls, desktop, computer screen and paper are shown in Figure 4. Luminous from the desktop, computer screen, and paper were also measured. Two diagonal lines were drawn on the desktop, computer screen and paper to select points to measure luminance. Then, two points on each line and the center points of the diagonal lines were chosen as measurement points of luminance levels of both the desktop and wall surfaces.

Figure 4. Measurement points for illuminance and luminance levels on indoor surfaces (**a**) Wall surfaces; (**b**) Desktop, computer screen and paper surfaces.



(**a**)



(**b**)

4. Research and Discussion

4.1. Illuminance, Luminous, and Subject Characteristics

In general, office occupants experience visual stimulation factors and perception under visual environments maintained at particular illuminance and luminous levels, and at certain color temperature of light sources. Figures 5–8 show the illuminance and luminous levels on the wall surfaces of the full-scale mock-up model space, when the target illuminance levels for the desktop were 500 lx and 750 lx. Overall, the illuminance and luminous levels were the lowest at the top of the desktop and increased with distance from the desktop due to the influence of parabolic louvers installed in the lighting fixtures. Differences in the illuminance and luminous levels on the three wall surfaces were insignificant, except at some points on the east and west walls.

Figure 5. Variation of illuminance on walls (500 lx condition).

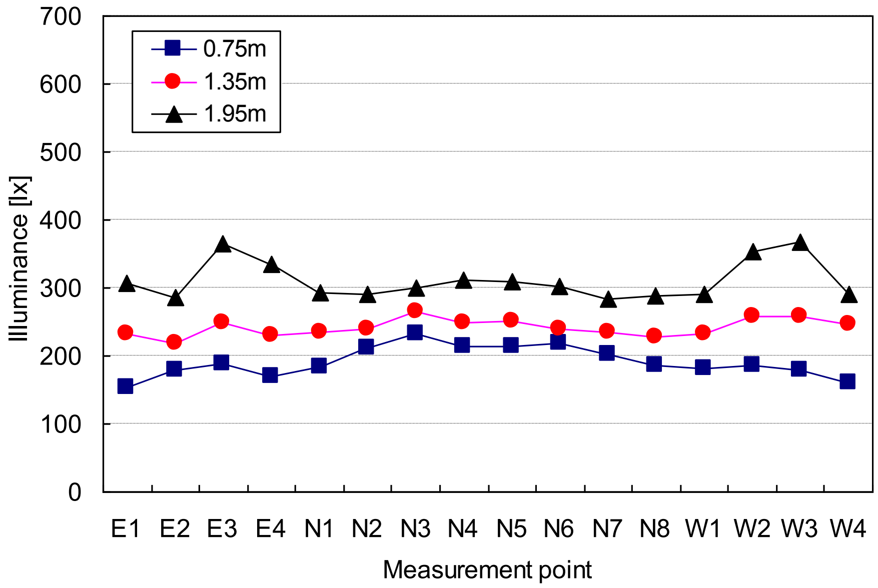
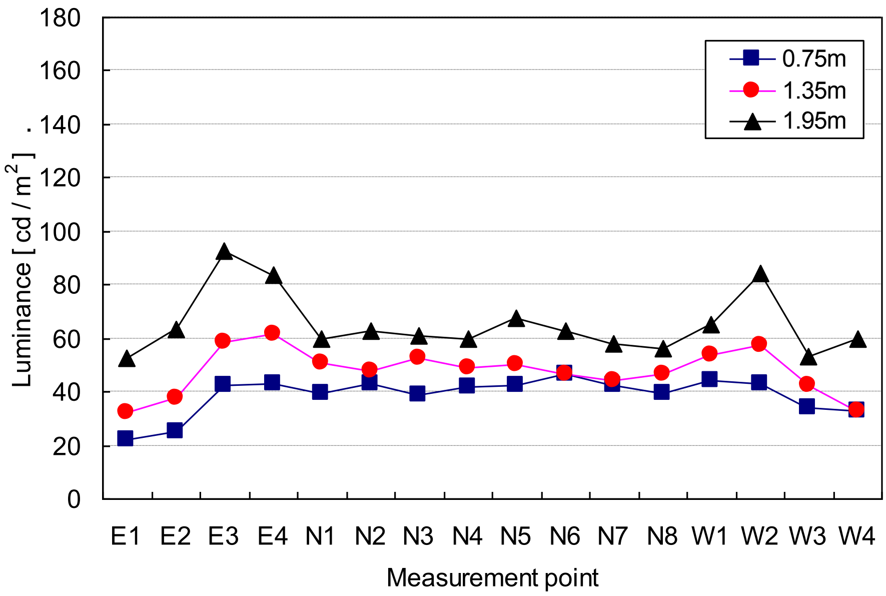


Figure 6. Variation of luminance on walls (500 lx condition).



For the 500 lx condition, the illuminance on the wall ranged from 154 lx to 368 lx. The illuminance levels at a height of 1.35 m from the floor ranged from 219 lx to 264 lx, which were equal to 43.8% and 52.8% of the target illuminance. The mean illuminance level on the north wall increased by 16.63% and 20.89% as the height from the floor increased from 0.75 m to 1.35 m and from 1.35 m to 1.95 m, respectively. The luminous level on the north wall was the background luminous level during the computer reading task. The luminous level on the north wall varied from 38.6 cd/m^2 to 67.4 cd/m^2.

For the 750 lx conditions, the illuminance on the north wall varied from 426 lx to 590 lx. The illuminance on the east and west walls varied from 259 lx to 415 lx, and 229 lx to 403 lx, respectively. The luminance on the north wall varied from 60.5 cd/m^2 to 94.1 cd/m^2. The mean luminous levels at the heights of 0.75 m, 1.35 m and 1.95 m on the north wall were 63.59 cd/m^2, 72.17 cd/m^2 and 89.72 cd/m^2, respectively.

Figure 7. Variation of illuminance on walls (750 lx condition).

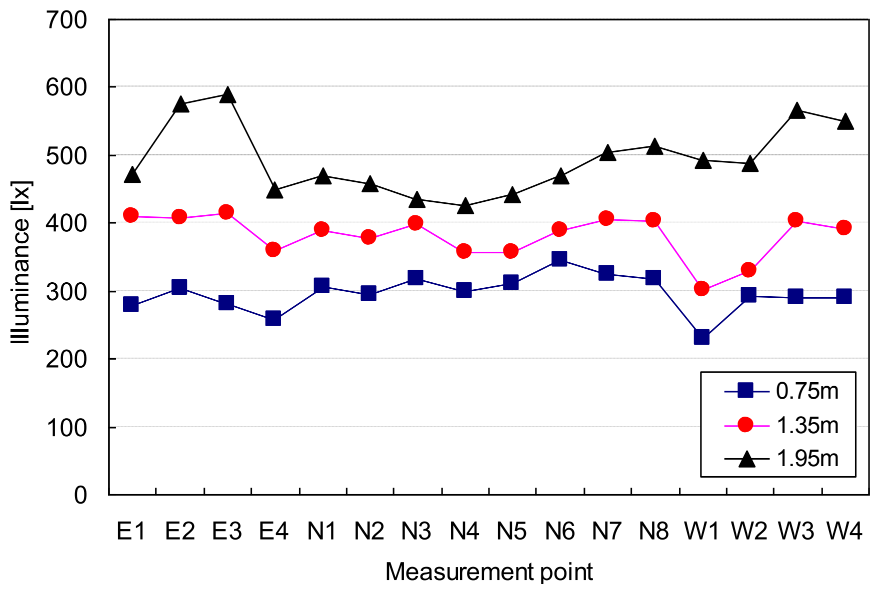
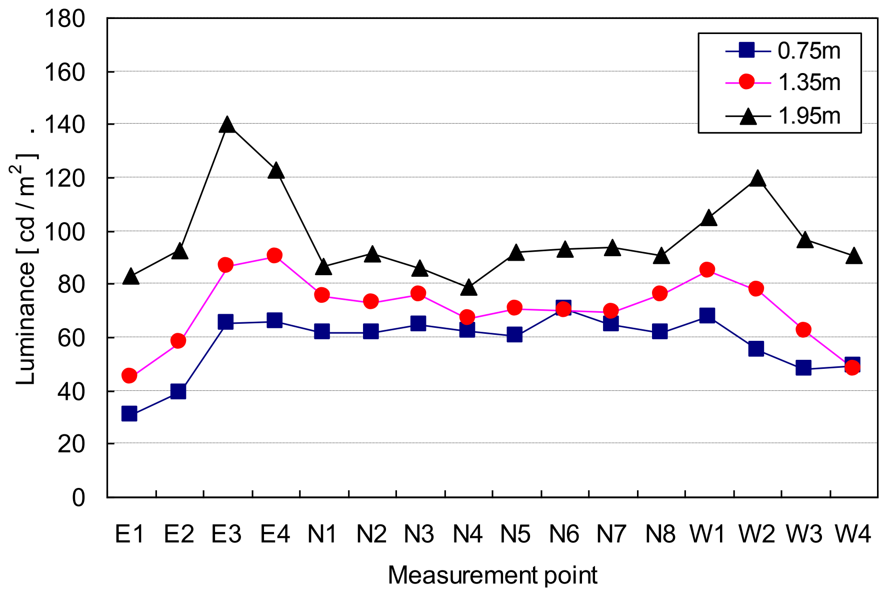


Figure 8. Variation of luminance on walls (750 lx condition).



Figures 9 and 10 show the luminous distribution on the desktop, paper, and the computer screen when the target illuminance levels on the desktop were 500 lx and 750 lx. For the 500 lx desktop illuminance condition, the luminous from the desktop surface varied from 29.36 cd/m^2 to 31.68 cd/m^2, while the luminous from the paper surface varied from 111.1 cd/m^2 to 114 cd/m^2. The contrast between the two surfaces was 2.63. The luminous projected from the computer screen ranged from 89.71 cd/m^2 to 125.5 cd/m^2.

For the 750 lx conditions, the luminous from the paper surface increased significantly compared with the luminous from the desktop. The mean luminous from the surfaces of the desktop and paper increased by 54.97% and 59.22%, respectively, compared to the 500 lx conditions. The contrast between the desktop and paper surface was 2.73. The mean luminous from the computer screen was 106.12 cd/m^2.

Figure 9. Variation of luminance on desktop and computer screen (500 lx condition).

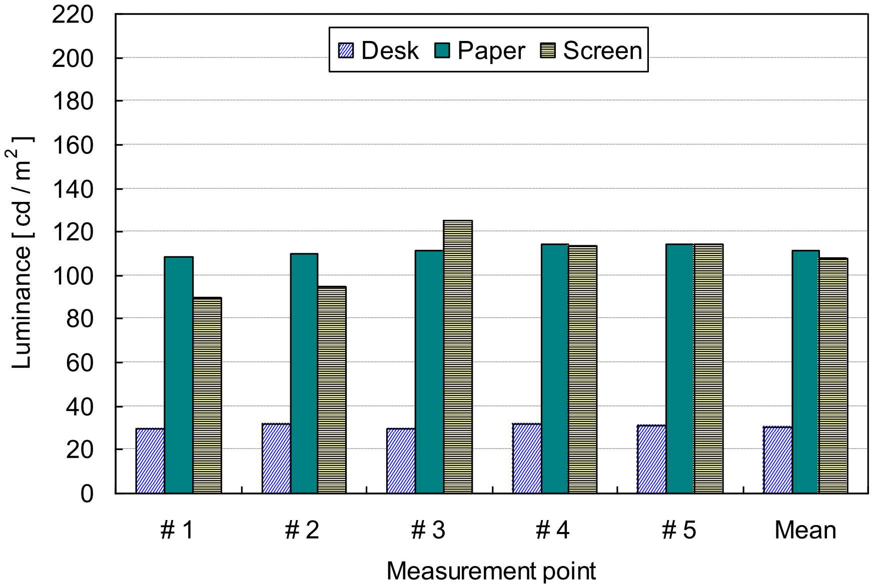
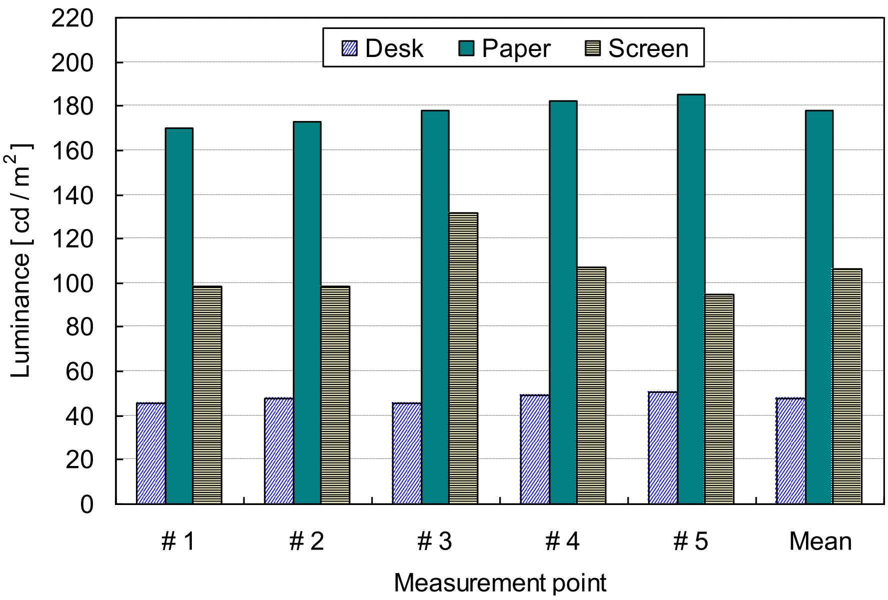


Figure 10. Variation of luminance on desktop and computer screen (750 lx condition).

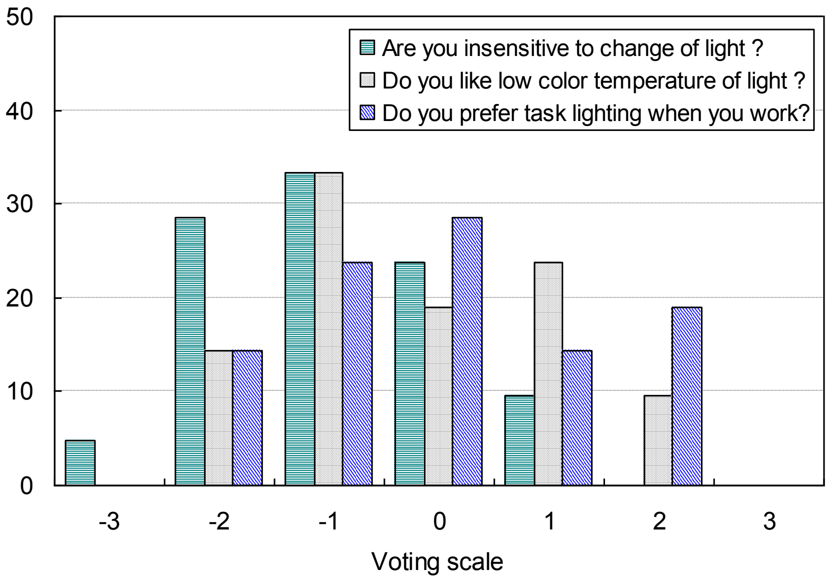


The illuminance and luminous on the walls influenced visual perception when reading tasks were conducted, since the visual fields of the subjects' eyes were not always confined to the area in which the reading materials were presented. For both target illuminance conditions, no critical problems relevant visual adaptation were observed when the subjects' eyes moved from the desktop to the walls, since the differences in illuminance between them were within ranges that satisfy photopic vision conditions. This implies that the reading tasks were not influenced by illuminance differences between the desktop and wall surfaces.

The subjects were nine male and 11 female undergraduate students with a mean age of 25. Six subjects wore glasses and five subjects wore contact lenses to correct their vision. The rest of the subjects had normal vision. None of the subjects were color blind. The subjects were experienced with conducting documentation tasks for 4 hours per a day using paper or computers.

Figure 11 shows subject sensitivities and preferences regarding lighting conditions. Overall, the subjects responded sensitively to lighting changes in the test space. It was found that 33.33% of the subjects were very sensitive to changes in the lighting environment while 33.3% of the subjects were slightly sensitive. Also, 23.1% of subjects were neutral, indicating that they were neither sensitive nor insensitive to lighting conditions.

Figure 11. Subjects' sensitivity and preference to indoor lighting environment.



While 33.33% of subjects preferred low color temperatures that generated reddish colors, 47.6% of subjects preferred high color temperatures associated with bluish light. It was found that 33.34% of subjects preferred task lighting when they performed tasks on the desktop, while 38.1% of subjects did not need task lighting for reading tasks. In summary, the general characteristics of subject preferences regarding lighting conditions did not show a significantly skewed distribution, although the distribution was not perfectly normal.

4.2. Perceptions of Visual Annoyance and Comfort

The perceptions of visual annoyance and comfort under different lighting conditions combined with three color temperatures, 3,000 K, 4,000 K and 6,500 K, and two illuminance levels, 500 lx and 750 lx were examined in this study. The subjects' visual perceptions of the six lighting conditions are shown in Figures 12–15. Each data point represents the mean of visual responses from all 20 subjects for each question.

Figure 12. Visual comfort and annoyance (500 lx, Computer task).

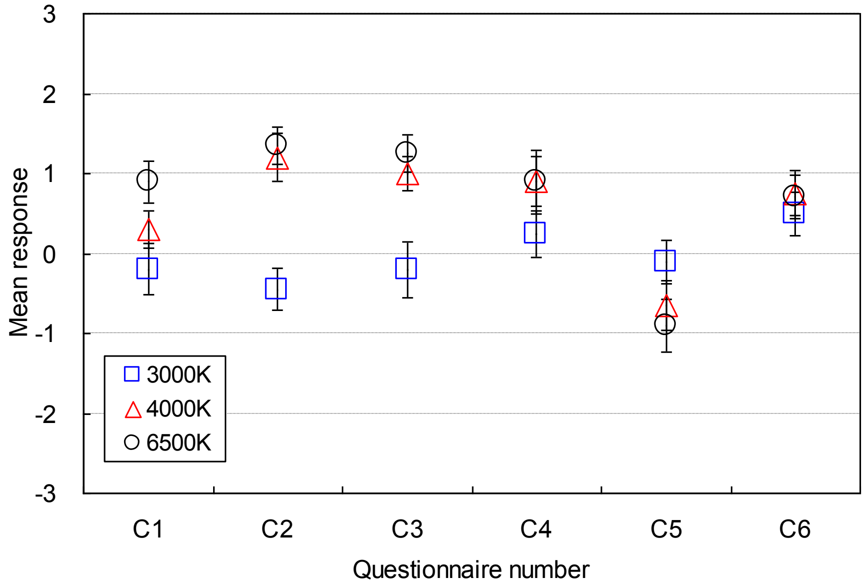
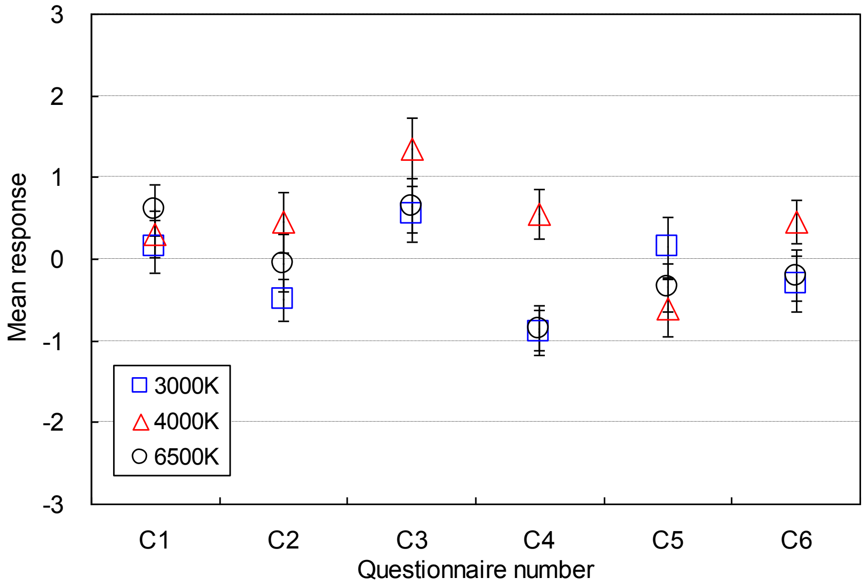


Figure 13. Visual comfort and annoyance (750 lx, Computer task).



Satisfaction (C1) with the color of light was reported under all conditions. Under the 500 lx conditions, subjects preferred the color of the 6,500 K lamps (M = 1.20, SD = 1.36), but their responses were near neutral to the color of the 3,000 K lamps, (M = 0.2, SD = 1.44). Under the 750 lx conditions, satisfaction with the color of light decreased. The decrease in the mean response for the paper task under the 3,000 K condition was noticeable, (M = −0.55, SD = 1.05) although the mean vote was still within an acceptable range.

The lighting conditions formed by the three color conditions maintained favorable visual environments under which subjects could see letters clearly for the reading tasks (C3). However, the 500 lx condition with the 3,000 K lamp was less favorable for paper-based reading tasks, (M = −0.40, SD = 1.35). The increase of illuminance was effective for paper-based reading tasks, but was not useful for the computer-based reading tasks since the increase of illuminance caused stronger background luminous levels that may cause glare.

Figure 14. Visual comfort and annoyance (500 lx, Paper task).

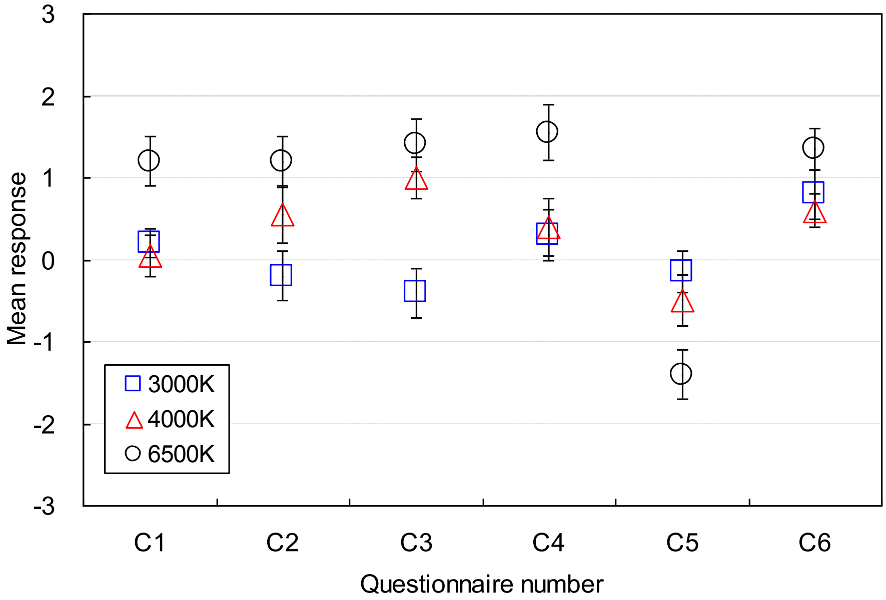
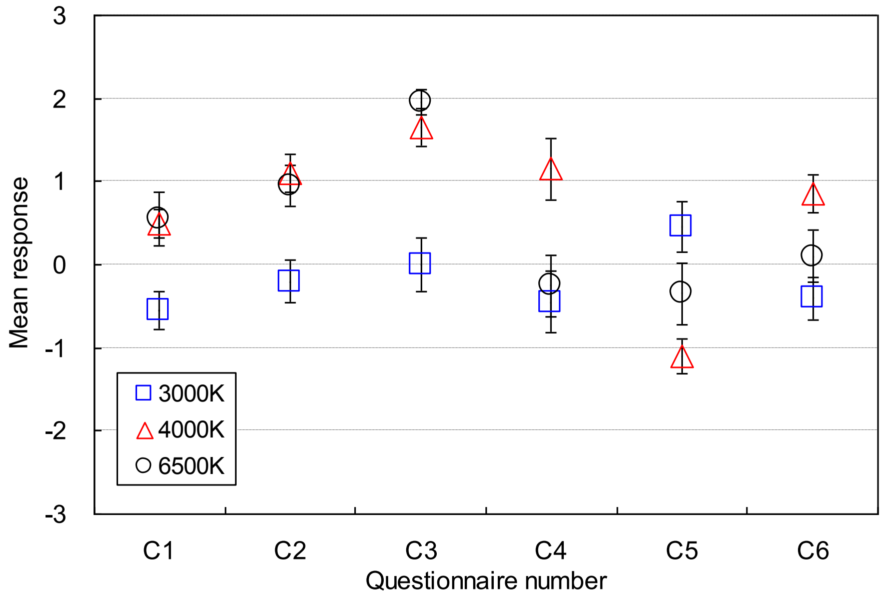


Figure 15. Visual comfort and annoyance (750 lx, Paper task).



Overall, the six lighting environments did not affect (C5) reading tasks significantly, except for the two cases under 750 lx. The disturbance was the greatest when the two target illuminance levels were kept under 3,000 K. The 4,000 K and 6,500 K conditions produced acceptable lighting conditions for computer-based and paper-based reading tasks.

Significant visual discomfort (C6) was not reported under any of the lighting environments used in this study. The 500 lx conditions were favorable for all color conditions in terms of visual comfort (M = 0.50, SD = 1.24~M = 1.36, SD = 1.09). The 6,500 K condition provided superior visual comfort for paper-based reading tasks compared with other conditions (M = 1.36, SD = 1.09). As the desktop illuminance increased to 750 lx, subjects reported lower visual comfort for the 3,000 K and 6,500 K conditions (M = −0.40, SD = 1.14~M = 0.10, SD = 1.41). However, better visual comfort was reported for paper tasks under 4,000 K (M = 0.85, SD = 1.04).

These results indicate that lamps with higher and lower color temperatures decreased visual comfort under the 500 lx condition, which is the minimum illuminance level for the performance of medium contrast or small size visual tasks in office environments [18]. In particular, 3,000 K lamps do not provide visual comfort in office environments. However, 4,000 K lamps are effective when the illuminance is greater than 500 lx.

These results might reflect the sensitivity of photoreceptors in human eyes. According to the characteristics of cone photoreceptors in the fovea and retina [18], the reddish color produced by lower color temperatures stimulate the photoreceptors more intensely than the bluish color produced by higher color temperatures. Therefore, the increase of luminance under lower color temperature conditions, such as 3,000 K, was sensed more sensitively and caused greater visual discomfort to subjects. This result is consistent with the original hypothesis of this study.

The results discussed in this section are valid for office environments where lighting conditions include a variety of color temperatures and illuminance conditions. These results also agree with those of previous studies. According to Knez, lower illuminance conditions are considered dim visual environments compared with higher illuminance conditions regardless of the color temperature of fluorescent lamps, and higher illuminance conditions were evaluated as more intense than lower illuminance conditions [6,8]. However, this previous study was confined to analyses of mood under different lighting conditions, and lacked analysis of the effects of stimulating factors on visual discomfort.

Manav showed that color temperature and illuminance levels influenced visual perception in office environments [3]. An illuminance level of 2,000 lx was preferred for comfort, spaciousness, brightness, and saturation evaluations. A color temperature of 4,000 K was preferred for favorable perceptions of visual comfort and spaciousness, and 2,700 K conditions were preferred for relaxed feelings in office environments. Under 2,000 lx conditions, occupants experienced direct or reflected glare, which causes significant visual discomfort, however visual discomfort was not analyzed in the study.

4.3. Perceptions of Visual Stimulation Factors and Mood

The perceptions of visual stimulation under each different color and illuminance conditions were examined. The mean responses to visual stimulation are shown in Figures 16–19. Overall, perception was influenced by changes of illuminance and color temperature. The visual perceptions of brightness or dimness for conducting reading tasks (VT3) were not significantly affected by color temperature when the desktop illuminance was 500 lx. The mean responses for the three color conditions ranged from −0.9 ($M = -0.9$, $SD = 0.72$) to −0.2 ($M = -0.2$, $SD = 1.06$) on the voting scale. In particular, the 3000 K condition was evaluated as a less bright visual environment when computer-based reading tasks were conducted.

As the illuminance changed to 750 lx, the influence of color temperature on the perception of brightness became stronger. In particular, the influence of 3,000 K conditions on computer-based reading tasks was noticeable ($M = 1.50$, $SD = 0.69$). The 6,500 K condition was a bright environment for paper-based reading tasks ($M = 1.10$, $SD = 1.07$), but its effect was weaker than that of 3,000 K. The perception of brightness for 4000 K was not significant although the mean response increased slightly.

Figure 16. Perception of visual stimulation (500 lx condition, Computer task).

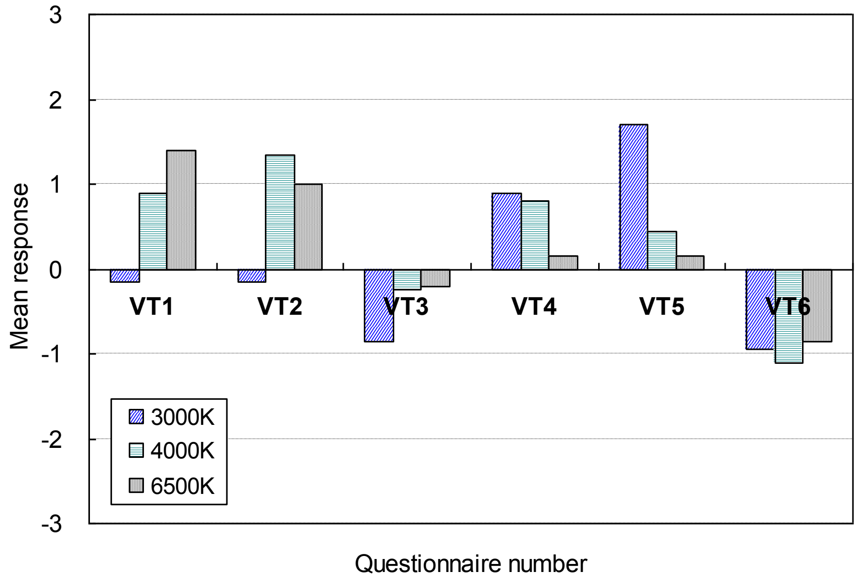
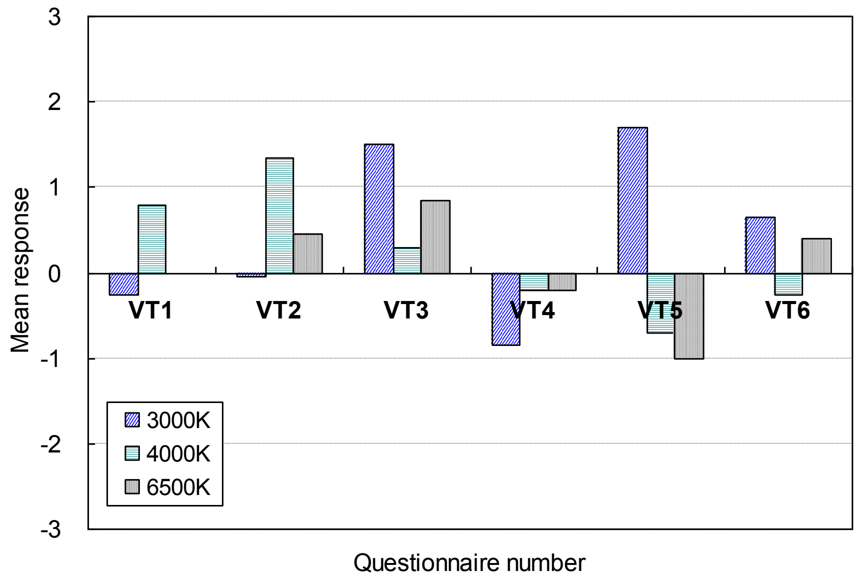


Figure 17. Perception of visual stimulation (750 lx conditions, Computer task).



This indicates that as illuminance increased beyond 500 lx, the perception of brightness was affected more strongly by long wave lengths in the visible spectrum than by short wave lengths that generate bluish light. Hence, this study recommends that 3,000 K conditions should not be used for office lighting, since 500 lx and 750 lx illuminance levels were evaluated as dim and bright environments, respectively, and therefore were not within the acceptable range. However, 4,000 K may be effectively used to reduce potential visual complaints, since the perception of brightness did not increase significantly as desktop illuminance increased to 750 lx.

Under the 3,000 K condition, the majority of subjects felt visually warm (VT5) but their visual perception was less favorable compared than for the other two conditions. Overall, the mean responses for visual perception under 3,000 K were within an acceptable range, below under which significantly worse perceptions were reported. However, the 3,000 K condition did not result in more favorable visual environments than the other two color temperature conditions. For instance, the perception of visual stimulation at 500 lx under the 6,500 K condition was effectively decreased. The 4,000 K condition also reduced visual stimulation, but not more than the 6,500 K condition.

Figure 18. Perception of visual stimulation (500 lx condition, Paper task).

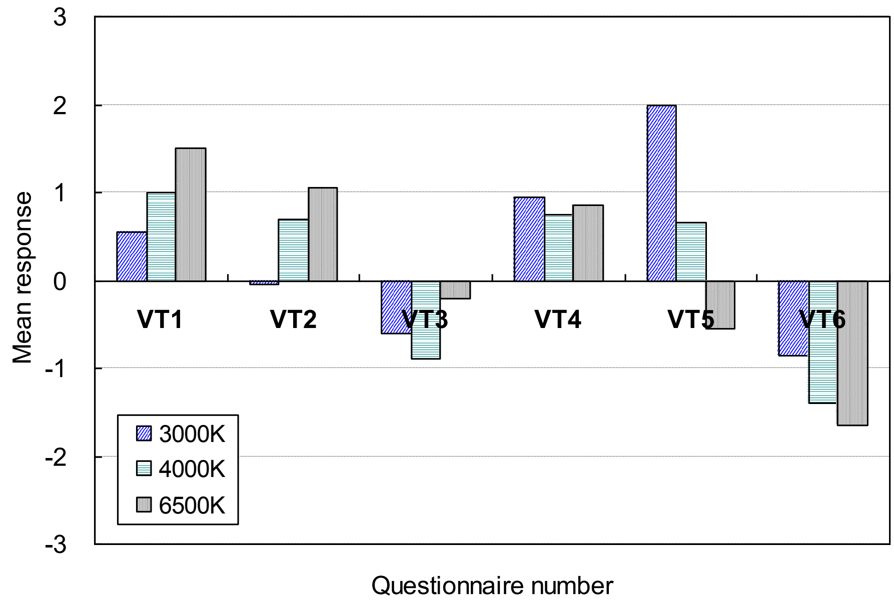
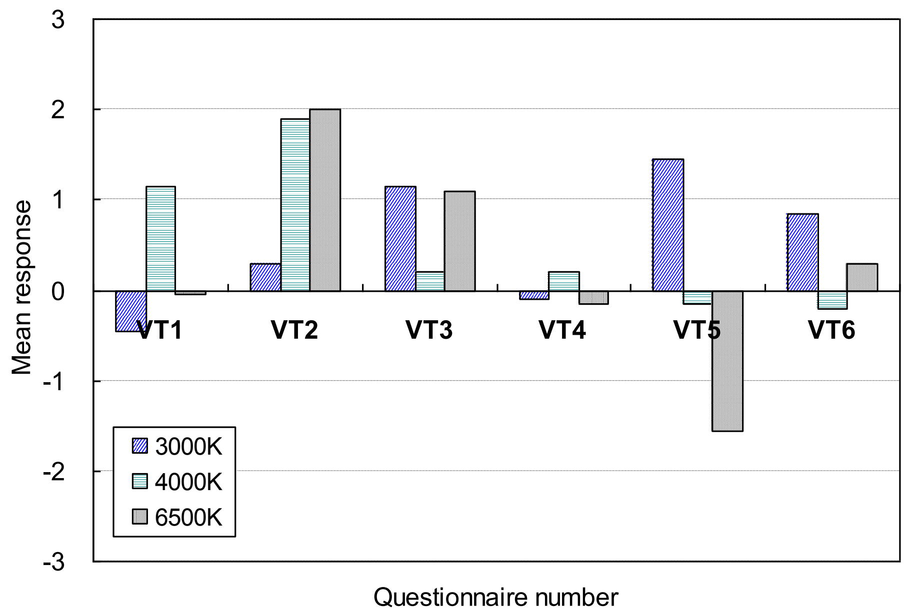


Figure 19. Perception of visual stimulation (750 lx condition, Paper task).



As the desktop illuminance increased to 750 lx under 6,500 K, the visual environment became slightly worse, and subjects felt stronger visual stimulation of the kind that potentially influences overall visual comfort. The 3,000 K condition decreased the mean response of visual perception within a very limited range. In comparison, the mean responses for 4,000 K imply more visually favorable perception. Therefore, the visual responses to visual stimuli vary according to color temperature and illuminance levels in the context of office lighting environments. The 4,000 K color temperature was suitable for 500 lx and 750 lx target illuminance conditions, and was associated with better visual perception.

The 500 lx illuminance condition caused no glare under all three color temperatures (VT6) (M = −1.65, SD = 1.31~M = −0.85, SD = 1.42). The weakest glare was reported under the 6,500 K condition. The lowest mean response occurred for 6500 K (M = −1.65, SD = 1.31), and the highest mean responses for 3,000 K and 6,500 K conditions (M = −0.85, SD = 1.42). As the desktop illuminance increased to 750 lx, the sensation of glare also increased. In particular, under 3,000 K the sensation of glare increased for the paper based-reading tasks to 0.85 from −0.95 on the rating scale (M = 0.85, SD = 1.04). The perception of glare was also affected by the 4,000 K and 6,500 K conditions, although the influence was not stronger than that of 3,000 K. The mean responses under 4,000 K and 6,500 K conditions were still within a comfortable range and no significant glare was perceived.

It appears that lower color temperatures containing longer wave lengths influenced visual perception of glare more than high color temperatures when office tasks were performed under desktop illuminance levels higher than 500 lx. In order to reduce the effects of glare, 3,000 K color temperatures should not be used for illuminance levels higher than 500 lx.

The variations of subject mood under each lighting condition are shown in Table 4. Overall, subject mood varied under the three color conditions according to illuminance and color temperature. No unfavorable moods were reported under 500 lx. The 3,000 K condition maintained favorable visual environments, and the subjects reported slightly better moods than for any other color conditions. In particular, the subjects felt that the lighting condition was cozy and attractive.

Table 4. Mood Perception under illuminance and color temperature conditions.

No.	Stats.	**Computer-based reading task**						**Paper-based reading task**					
		500 lx			750 lx			500 lx			750 lx		
		3,000 [K]	4,000 [K]	6,500 [K]	3,000 [K]	4,000 [K]	6,500 [K]	3,000 [K]	4,000 [K]	6,500 [K]	3,000 [K]	4,000 [K]	6,500 [K]
M1	Mean	0.05	0.40	0.35	−1.00	0.65	0.15	0.75	0.20	1.15	−0.40	0.90	0.05
	SD	1.39	1.23	1.31	1.21	1.57	1.14	1.25	1.20	1.23	1.23	1.12	1.23
M2	Mean	0.25	0.50	0.60	−0.80	0.35	0.05	0.60	0.10	0.85	−0.55	0.55	0.10
	SD	1.29	1.10	1.54	1.28	1.60	1.43	1.47	1.02	1.27	1.10	1.00	1.33
M3	Mean	0.35	0.25	0.45	−0.15	−0.30	−0.15	0.90	−0.20	0.15	−0.40	0.55	−0.05
	SD	1.14	1.52	1.61	1.66	1.42	1.31	0.97	1.20	1.35	0.99	0.76	1.54
M4	Mean	0.80	0.90	0.75	−0.55	−0.30	−0.20	0.85	0.90	0.40	−0.20	0.30	−0.45
	SD	1.47	1.02	1.02	1.64	0.98	1.01	1.60	1.02	0.94	1.15	0.86	0.94
M5	Mean	−0.05	1.10	1.55	−0.25	1.20	0.35	1.30	1.65	1.15	0.60	1.70	0.60
	SD	1.64	1.17	1.61	1.25	1.32	1.42	1.59	1.09	1.09	1.10	1.13	1.14
M6	Mean	1.15	0.65	0.70	−0.15	−0.75	−0.30	0.90	0.60	−0.10	0.20	0.20	−0.25
	SD	1.31	1.04	1.03	1.35	1.25	1.17	1.62	0.88	1.07	1.01	1.11	1.45
M7	Mean	−0.55	0.05	0.35	−0.65	0.85	0.15	−0.45	−0.25	0.40	−0.40	0.45	1.25
	SD	1.19	1.15	1.14	1.31	1.31	1.23	1.23	1.02	1.47	1.43	0.89	1.52

The mean responses for mood for the 3,000 K and 6,500 K conditions became lower on the voting scale at 750 lx. The decrease for 3,000 K was noticeable but not significant. Slightly better moods were reported when computer-based reading tasks were performed at 4,000 K. In summary, subject mood was affected by color temperature and illuminance. Lower color temperatures such as 3,000 K were more effective for producing better moods at lower illuminance levels. However, higher color temperatures were preferred at 750 lx.

The results of this study are valid for office environments in which lighting conditions include a variety of color temperatures and illuminance conditions. These results generally agree with those of previous study [3]. Manav found that the 3,000 K condition at 500 lx made subjects feel relaxed. The 3,000 K color temperature felt visually warm, while the 6,500 K conditions made subjects feel tense and visually cold. While Manav used an illuminance of 2,000 lx for experiments, 500 lx and 750 lx, which are more common in office lighting conditions were used in this study. Although the illuminance levels used for Manav and the present study were different, the visual perceptions of color temperature conditions reported by subjects were similar.

According to Knez [8,9], 4,200 K fluorescent lamps made the test space brighter than did 2,950 K lamps. The 4,200 K condition at 300 lx and 2,950 K condition at 1,500 lx were associated with more positive moods by subjects. However, Knez analyzed only mood under different lighting conditions, and not the effects of stimulating factors on visual discomfort, as in the present study. Knez *et al*. [6,10] stated that younger adults (average 23 years of age) most often experienced negative moods in more reddish color temperatures such as 3,000 K, while mood was more positive under bluish color conditions at 4,000 K when cognitive tasks were performed. They also showed that glare was perceived under 1,500 lx independent of color temperature, but glare was not discussed in terms of visual discomfort.

In the present study, similar results to those of Knez under three color temperature conditions were observed. The perception of glare was strongly relevant to visual discomfort at 750 lx regardless of color temperature. The 3,000 K condition was preferred as it resulted in a better mood, while 6,500 K was the least preferred.

Kim *et al*. [15,16] stated that increases in illuminance decrease visual perception in office environments lighted with 5,000 K fluorescent lamps. As illuminance increases beyond 500 lx, the perceptions of brightness and glare became strong, and negatively impact visual comfort. In addition, feelings of eye fatigue, distraction, inability to see letters clearly, and visual annoyance are important influential factors that affect visual comfort in office environments.

The results of previous studies are therefore generally consistent with the results of the present study, in which the perception of visual comfort was strongly influenced by visual distraction and stimulation, glare, and degree of visual annoyance due to light. Stimulating factors that impair visual comfort and perception in office environments were examined in all of these studies. The results of these studies imply that visual comfort is not improved unless factors that impede visual perception are effectively reduced under office lighting conditions.

4.4. Prediction Models for Visual Annoyance and Mood

Prediction models that explain the influence of visual stimulation factors on the perception of visual comfort were developed in this study to examine relationships between them. The response of visual comfort (C6) was considered as a dependent variable, and the visual stimulation factors that affect visual response were considered as independent variables in the prediction models. All answers regarding stimulation factors from questionnaires were included in initial multiple linear regression models as independent variables. Only independent variables that were acceptable given a significance level of 0.05 were included in final models.

Analysis of variance (ANOVA) was employed to examine linear relationships between independent and dependent variables. The prediction models expressed by multiple linear regressions are summarized in Table 5. Overall, the linear regression models show that perceptions of visual comfort (C6) for reading tasks and visual stimulation factors under given lighting conditions are linearly correlated. The coefficients of determination (r^2) of the prediction models varied from 0.6073 to 0.7649. This implies that the reduced error variances in the sensation of visual comfort under the given lighting conditions ranged from 60.73% to 76.49%, when visual stimulation factors were utilized to predict the perception of visual comfort.

Table 5. Prediction model of visual comfort for lighting environment.

Color temperature	Variable	Unstandardized Coefficients		*t*	Sig.	ANOVA
		B	Std. Error			
3,000 K	(Constant)	0.18	0.10	1.80	0.08	F (3,76) = 39.18, Sig. = 0.00, r^2 = 0.6073
	Q1	−0.43	0.06	−6.30	0.00	
	Q3	0.45	0.08	5.27	0.00	
	M9	0.24	0.07	3.28	0.00	
4,000 K	(Constant)	0.15	0.09	1.68	0.10	F (4,75) = 29.13, Sig. = 0.00, r^2 = 0.6084
	Q2	−0.28	0.08	−3.17	0.00	
	Q3	0.39	0.08	4.60	0.00	
	Q6	−0.34	0.07	−4.91	0.00	
	M6	0.13	0.05	2.40	0.02	
6,500 K	(Constant)	−0.35	0.11	−3.05	0.00	F (5,74) = 48.07, Sig. = 0.00, r^2 = 0.7649
	Q1	−0.30	0.07	−4.16	0.00	
	Q2	0.24	0.08	2.73	0.01	
	Q3	0.35	0.07	5.08	0.00	
	M6	0.17	0.07	2.22	0.03	
	M7	0.30	0.07	3.95	0.00	
	Q4	0.50	0.08	5.91	0.00	
	Q6	−0.37	0.08	−4.60	0.00	

The perception of glare (VT6), satisfaction with the color of light (C1), sensation of being bothered by light (C5), visual distraction (C2), and feelings of dimness or brightness (T5) were primary influential factors that affected the perception of visual comfort. The satisfaction with the color of light (C1) was an important factor in the prediction of visual comfort under all lighting conditions. The perception of visual comfort was linearly proportional to the satisfaction with the color of the light source.

The perception of glare (VT6) was a strong contributor to the perception of visual comfort at 3,000 K and 6,500K, but became weaker at the 4,000 K. The 3,000 K and 6,500 K conditions that generated red and bluish spectra were more irritating to subjects than were 4,000 K conditions that contain less red and bluish spectra.

These results appear to be relevant to the perception of satisfaction with the color of light (C1) and visual distraction (C2) under both lower and higher color temperature. Visual stimulation was reported at 3,000 K, and distraction was reported at 6,500 K. The satisfaction with the color of light (C1) and perception of being bothered by light (C5) were influential contributors to visual comfort for reading tasks under 4,000 K conditions.

The sensation of brightness or dimness (VT3) in lighting environments was also a meaningful influential factor to the perception of visual comfort under 4,000 K and 6,500 K. This indicates that office spaces should be bright, in order to improve visual comfort for office tasks, at 6,500 K. However, less bright environments are necessary for better visual comfort at 4,000 K.

The perception of eye fatigue (C4) was reported along with visual distraction at 6,500 K. Eye fatigue was less influential on visual comfort than was the perception of visual distraction. The effects of eye fatigue on visual comfort were also reported at 4,000 K, although they were slightly weaker than under 6,500 K.

The ANOVA results for mood prediction shown in Table 6 indicate that the prediction models in this study were acceptable at a significance level of 0.01, and that an appropriate linear relationship existed between independent and dependent variables. Compared with a prediction model of visual comfort, less reduction in error variation occurred for the prediction of mood, since the coefficients of determination (r^2) varied from 0.4454 to 0.6104.

Table 6. Prediction model of mood for lighting environment (mood: pleasant/unpleasant).

Color temperature	Variable	Unstandardized Coefficients		*t*	Sig.	ANOVA
		B	Std. Error			
3,000 K	(Constant)	−0.07	0.12	−0.62	0.53	F (3,76) = 20.35, Sig. = 0.00, r^2 = 0.4454
	Q2	−0.37	0.09	−3.76	0.00	
	Q4	0.40	0.09	4.38	0.00	
	M8	0.22	0.08	2.59	0.01	
4,000 K	(Constant)	−0.31	0.13	−2.36	0.02	F (2,77) = 43.77, Sig. = 0.00, r^2 = 0.5320
	Q3	0.42	0.09	4.34	0.00	
	Q5	0.45	0.08	5.36	0.00	
6,500 K	(Constant)	−0.12	0.11	−1.12	0.27	F (2,77) = 60.32, Sig. = 0.00, r^2 = 0.6104
	Q4	0.50	0.08	5.91	0.00	
	Q6	−0.37	0.08	−4.60	0.00	

Overall, the perception of visual comfort (C6) and visual annoyance (C5) strongly affected the perception of lighting conditions as pleasant. Subjects who experienced greater visual comfort and less annoyance also felt that the lighting environment was more pleasant. In particular, the influence of visual comfort on pleasantness was the strongest at 6,500 K, when less visual annoyance (C5) due to lighting conditions increased perceptions of pleasure.

For the 3,000 K conditions, the ability to see letters clearly (VT2) was also a contributor to the perception of pleasantness. The satisfaction with the color of light (C1) was a meaningful contributor at 4,000 K. Visual annoyance (C5) was reduced at 6,500 K and produced better visual environments in which occupants experienced more pleasure. This implies that improved visual environments, where occupants can easily distinguish letters on paper or on a computer screen are necessary to improve the perception of pleasantness.

In summary, the prediction models imply that the less the subjects were visually bothered by the light required for their tasks, the more visual comfort they felt. The color of the light source should be carefully chosen to maintain favorable visual environments for office surroundings, since color predicts visual comfort.

The results of this study imply that the illuminance levels produced by 3,000 K lamps should not exceed 500 lx to improve visual comfort in office environments. At 6,500 K, visual distraction and glare were important factors that should be carefully considered to mitigate the perception of visual discomfort for office tasks. In order to reduce visual discomfort at 4,000 K, careful attention should be paid to the visual annoyance that may be caused by light.

The most influential factor on mood was visual comfort, which was important under most of the lighting conditions examined in this study. Additional factors affecting mood response were the color of light and visual stimulation factors such as stimulation and distraction. A comprehensive consideration of the color and visual stimulation factors involved in lighting design would be useful to improve visual environments for office tasks.

5. Conclusions

This study was performed in order to analyze the influence of the combined effects of color temperatures and illuminance levels of light sources on visual perception and mood responses in a small office space. The summary of findings is as follows:

(1) Visual environments formed by fluorescent lamps with lower color temperatures, such as 3,000 K, caused sensations of glare and resulted in visual discomfort when paper-based and computer-based reading tasks were performed under target illuminances higher than 500 lx. Lamps with 3,000 K color temperatures are not recommended for use in office spaces.

(2) All three color temperature conditions used in this study reduced the perception of visual discomfort at 500 lx compared to 750 lx. Under the three different color temperatures, the visual perception of visual stimulation factors caused by different lighting environments was influenced according to increases of desktop illuminance. Dissatisfaction with visual perception caused by visual stimulation factors was effectively mitigated when 4,000 K color temperatures were used at 500 lx and 750 lx, and when 6,500 K color temperature was used at 500 lx. Lamps with 4,000 K color temperatures were effective at illuminances higher than the minimum levels recommended by guidelines.

(3) Subject mood was influenced by color temperature and illuminance level. The 3,000 K condition was associated with better moods at 500 lx than other color temperatures. However, 3,000 K was not recommended for office tasks relevant to visual performance. The 4,000 K color temperature was associated with better mood under a 750 lx target illuminance. Therefore, 4,000 K conditions are recommended for visual environments in office spaces where the target illuminance is greater than or equal to 500 lx.

(4) Multiple regression analyses suggest that visual stimulation factors should be mitigated in lighting environments in order to improve visual comfort for general office duties, such as computer-based and paper-based reading tasks. Subject satisfaction with the color of light sources is critical for the prediction of visual comfort. In order to maintain favorable lighting environments regarding mood, lighting conditions must ensure visual comfort and prevent visual annoyance. Visual stimuli that prevent occupants from distinguishing letters clearly

should be minimized. Lighting conditions that ensure satisfaction with the color of the light source are preferred because they are associated with better mood in office spaces.

This study was performed in a full-scale mock-up office space. Although the space was furnished like a real office, the environments and tasks were not exactly the same as those performed in real office spaces. This might have subconsciously influenced the subjects and therefore impacted visual perception. Tests in real-life settings would be beneficial for future studies. The results of this study are based on responses from a limited number of subjects. Also, the voting scale for answering questionnaires is based on the semantic differential method. Due to the limited number of subjects participated in tests using the semantic differential method, there might be a potential barrier to generalize the result of this study. In a future study, responses from more diverse subjects would be preferred to provide more reliable results.

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Author Contributions

All authors participated in preparing the research from the beginning to ends, such as establishing research design, method and analysis. All authors discussed and finalized the analysis results to prepare manuscript according to the progress of research.

Conflicts of Interest

The authors declare no conflict of interest.

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