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Analyses on Human Responses to Illuminance Variations for Resident-Friendly Lighting Environment in a Small Office

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Key Words
Illuminance variation · Visual perception · Mood · Visual annoyance · Fluctuation range · Dimming system

Abstract
This study examines the influence of illuminance variation on visual perception and mood in a small office. Field measurements and annoyance tests were performed in a full-scale mock-up office space. Subjects conducted paper-based and computer-based reading tasks when six instantaneous fluctuation ranges were given under 500 lx and 650 lx base level conditions. Results indicate that equal amounts of instantaneous illuminance fluctuation could influence visual perception differently under these two base level conditions. Visual annoyance under the 500 lx base level was more severe than that under the 650 lx base level. The acceptable illuminance fluctuation ranges that did not cause visual annoyance under 500 lx base level conditions were 141.3 lx for paper-based tasks and 187.3 lx for computer-based tasks. Under 650 lx base level conditions, the acceptable ranges were 200.3 lx and 252.4 lx for paper-based and computer-based tasks respectively. The mean mood and perception responses for visual thresholds under the 650 lx base level showed more positive feelings than those under the 500 lx base level. Multiple linear predictive models showed that feelings of visual sensitiveness to illuminance variation, visual distraction, and stimulation were significant contributors to visual annoyance under fluctuating illuminance conditions.

Introduction

Dimming control systems that control electric light output instantaneously have been used in buildings to keep target illuminance in workplace areas and save lighting energy. The systems are considered to function effectively when they meet target illuminance within recommended illuminance ranges using optimum electric light. A variety of studies have been performed under

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various daylight and electric conditions to propose optimum strategies for the lighting control systems that save lighting energy and satisfy occupants' visual needs in space [1–7].

In general, the dimming systems control light output from lighting fixtures based on signals generated by sensors that detect the variation of light within short time periods. The fluctuation of light output results in frequent changes of illuminance on indoor surfaces such as workplanes and walls. Under this condition, occupants have to adapt their eyes repeatedly to the changing luminous environment, and this repetitive adaptation procedure causes visual stimulation and eye fatigue. Accordingly, unstable visual environments that potentially cause visual annoyance and discomfort to occupants are produced due to the fluctuation of light.

The fluctuation of illuminance level within a short period functions as an intensive visual threshold and would influence visual perception negatively when the dimming control systems are used in office buildings. The visual perception influenced by the changes in lighting could affect mood and visual comfort which could potentially impair the performance of office workers.

In general, lighting energy savings was considered to be the most important factor when the dimming systems were applied to buildings. The utility costs, including lighting energy in office buildings were less than one percent of the overhead used to pay office workers [8, 9]. However, there has not been sufficient attention paid to the influence on visual perception of illuminance variation controlled by systems which can have an effect on eye health [10].

Therefore, this study examines the influence of the visual environment formed by frequent illuminance variation on visual perception in a small office to propose optimum controls of illuminance that would ensure occupants' visual comfort and mood. Tests of visual annoyance and mood responses were performed in a full-scale mock-up office space under a variety of fluctuating illuminance conditions.

Research Hypothesis

Two factors were hypothesised to examine occupants' visual perception and mood responses. The primary hypothesis considered in this study is that visual responses and mood are influenced by illuminance variation. It is expected that occupants would experience more visual stimulation and annoyance when the variation range of illuminance is greater, which could result in significant visual annoyance and negative mood.

The secondary hypothesis is that the equal amount of lighting variation could influence occupants' visual responses differently when the variation occurs for different reading tasks under different task illuminance conditions. It was expected that lighting variation would occur at a high task illuminance level, which could cause weaker levels of visual stimulation and annoyance to occupants. The influence of lighting variation on visual annoyance and mood response was also expected to be weaker for computer-based reading tasks than for paper-based reading tasks.

The human visual system would repeatedly adapt to varying luminous environments to perceive objects, but the frequent change of lighting in a short time period could generate visual annoyances with thresholds that could result in visual dissatisfaction. The change of illuminance is not perceived equally under different task conditions and luminous environments. Equal illuminance changes for different tasks and illuminance would generate different levels of visual perception according to the background illuminance conditions that form the overall luminous environment in space. Worse visual perception and mood responses are expected when paper-based tasks are performed under lower task illuminance.

Research Methods

Test Space and Lighting Systems

A series of subjective studies of visual comfort was performed in a full-scale mock-up office space, which was specially designed and constructed for the evaluation of the lighting system in a variety of control settings. The dimensions of the space were 3 m wide $\times$ 3.6 m deep $\times$ 2.4 m high. The detailed dimensions of the room are shown in Figure 1. The space was furnished as a small office for private use, and no windows were installed. White wall paper was installed on the wall, and light blue carpet was installed on the floor. An array of 0.6 m $\times$ 0.6 m suspended grids covered with white acoustic panel boards was installed on the ceiling.

A desk and chair were placed in the space. The dimensions of the desk were 1.8 m long $\times$ 0.75 m wide $\times$ 0.75 m high, which was designed for personal use. The edges of the desk were 0.9 m away from the east and

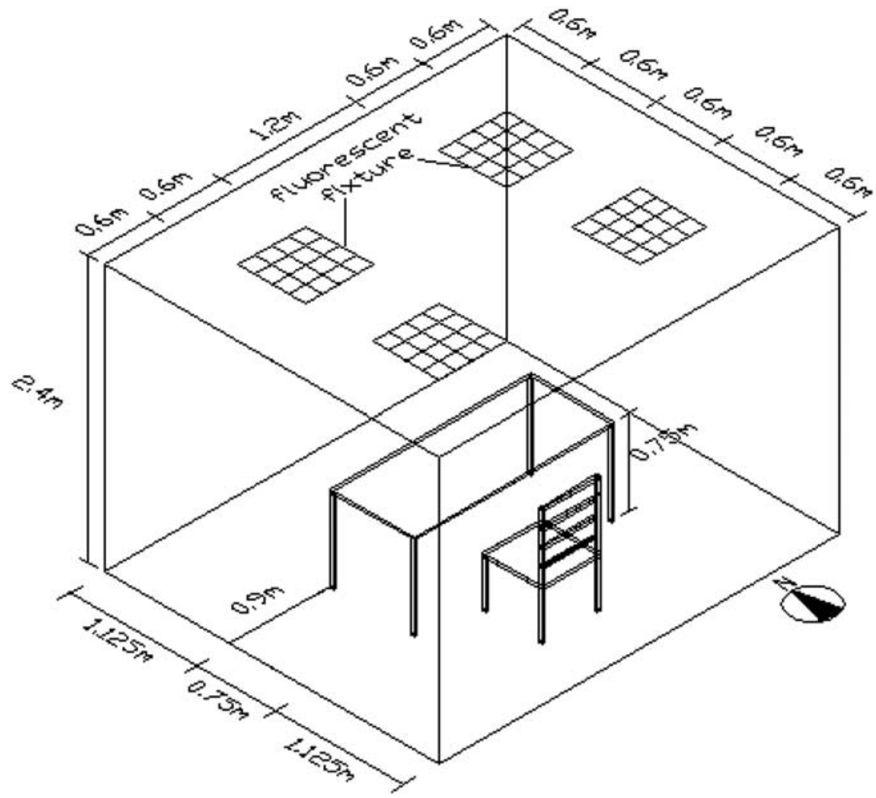

Fig. 1. Layout of full-scale mock-up model.

west walls so that the centre of the desk overlapped with the geometrical centre of the space. The desktop was covered with a dark brown wood surface, and no specular reflection occurred from the surface. A 19-inch computer monitor with a resolution of 1024×768 pixels was placed at the centre of the desktop for office tasks given in this study.

A recessed fluorescent lighting fixture was installed on the ceiling of the space. The fixture had dimensions of $0.6\,m \times 0.6\,m$ with two U-shaped fluorescent lamps consuming 32 W per lamp. The fixture had a parabolic fluorescent troffer with 7.5 cm louvers, which direct light distribution. The colour temperature of the lamp was 5000 K according to the specification sheets provided by the manufacturer.

Mean illuminance on the desktop surface formed by the four lighting fixtures was 900 lx. Because the illuminance level was too great for general office tasks, a lighting controller that dims the light output from the fixture was installed to control the desktop illuminance. The target illuminance levels on the desktop set up for base cases in this study were 500 lx and 650 lx.

Subjects and Questionnaires

Test subjects were recruited among college and graduate students. Overall, 36 students ages 20 to 45 participated in the study. The subjects were pre-screened to satisfy criteria such as having normal vision and health, and with no colour blindness. All of the subjects were used to perform office tasks such as documentation using paper, computer typing and software applications.

When subjects arrived at the test site, pre-instructions were given before the main test began. They were asked to sign a consent form and detailed instructions were given to the subjects explaining how the tests would be performed, including detailed definitions of terminology such as visual comfort, glare, annoyance and mood perception. Subjects were informed that the data would be kept confidential, and that they could stop participating in the survey if they wanted to at any time during the experiment. Next, the general questionnaires were answered by the subjects. During the pre-instruction, each subject had enough time to adapt to the new visual environment in the test space before the main visual annoyance test began.

The questionnaires for the visual annoyance test in this study were used to assess the general information about

Table 1. Survey questionnaires

Light condition	Test	Question number	Question content
Constant	Annoyance	A1	Overall, is the light distributed well?
		A2	Does the electric light cause glare that bothers your computer task?
		A3	Does the electric light cause glare that bothers your paper task?
		A4	Overall, is the light bright enough for your computer task?
		A5	Overall, is the light bright enough for your paper task?
		A6	Are you satisfied with the current lighting condition?
		A7	Do you want to increase electric light to improve your visual satisfaction?
	Temporary mood and visual threshold	M1	Does the light make you like the space?
		M2	Does the light make you feel pleasant?
		M3	Does the light make you feel relax?
		M4	Does the light make the room feel attractive to you?
		M5	Do you feel no fidgety at all?
		M6	Do you feel no eye fatigue?
		M7	Do you feel no visual distraction?
		M8	It is not difficult to see a letter.
		M9	Do you feel no visual stimulation?
Fluctuating	Annoyance	FA1	Overall does the change of light bother you?
		FA2	Are you satisfied with the change of electric light?
		FA3	Is the light change visually sensitive to you?
		FA4	Do you prefer to keep light constant for your reading task?
	Temporary mood and visual threshold	FM1 . . . FM9	Each question is equal to that under constant light conditions respectively (ex, FM1 = M1, FM2 = M2...... FM11 = M11, etc.)

the subjects such as gender, age, eyesight and colour blindness, visual and mood perceptions under constant illuminance conditions, and visual annoyance tests under varying illuminance conditions were also investigated. The questionnaires are summarised in Table 1.

Questionnaires relevant to subjects' preferences regarding the light sources and illuminance levels, and sensitiveness to glare and colour of the lighting were included. The questionnaires that assessed constant illuminance conditions included visual responses such as the subjects' visual feelings, overall evaluations, and satisfaction with the lighting condition. Ten mood responses according to visual sensation were also included in the questionnaires.

The questionnaires about annoyance under instantaneous fluctuation conditions included four questions pertaining to perceptions of annoyance and comfort, satisfaction with and sensitiveness to the changes of light, and preference for constant illuminance levels. The same questionnaires were used to assess mood responses under constant illuminance conditions as well as under the fluctuation conditions.

Dimming Control Scenario, Visual Annoyance Test and Data Monitoring

Several step dimming scenarios that controlled desktop illuminance over short periods of time were set up to evaluate the influence of fluctuating illuminance on visual responses and mood perception when performing office tasks, such as computer-based and paper-based reading tasks.

First of all, 500 lx and 650 lx illuminance levels were initially set up for the desktop. Six fluctuating ranges ($\delta_{i,i=1,6}$) were determined by the step dimming control scenarios for the desktop illuminance level. They were denoted as $\delta_1 = 50$ lx, $\delta_2 = 100$ lx, $\delta_3 = 150$ lx, $\delta_4 = 200$ lx, $\delta_5 = 250$ lx and $\delta_6 = 300$ lx. The desktop illuminance varied within a fluctuating range ($\delta_{i,i=1,6}$) under 500 lx and 650 lx illuminance levels that were initially set up on the desktop. The procedures with a 650 lx illuminance for office tasks were as follows:

- Step 1:

The lighting system was initially set to provide a base level illuminance of 650 lx on the desktop. After 10 min, the subjects were asked to answer questionnaires regarding how they felt about the constant lighting condition.

- Step 2:

Desktop illuminance was immediately increased to a base level of $650 + \delta_{i=2}$ plus an increasing range, and decreased to the base illuminance level of 650 lx again after 30 s. This procedure was repeated three times. After that, the subjects were asked to evaluate how much they were visually annoyed by the change of illuminance. While the subjects answered, the desktop illuminance level was set at 650 lx. The subjects were then given 2 min to prepare for the next procedure.

- Step 3:

The test procedures described in Step 2 were repeated for the order of $\delta_5 = 250$ lx, $\delta_1 = 50$ lx, $\delta_3 = 150$ lx, $\delta_6 = 300$ lx and $\delta_4 = 200$ lx.

Steps 1, 2 and 3 were repeated for paper-based and computer-based reading tasks, respectively. Once the annoyance tests under the 650 lx base level illuminance were completed, the desktop illuminance level in Step 1 was set at 500 lx and the Steps 1, 2 and 3 were repeated. The patterns of illuminance on the desktop under the 500 lx base level conditions are shown in Figure 2.

For the visual annoyance test designed in this study, paper-based and computer-based reading tasks that are typically performed in offices were given to subjects to simulate general office duties under each dimming control scenario. For reading tasks, a variety of paragraphs were prepared in advance using Microsoft Word. The contents of paragraphs were drawn from contemporary news articles. The font type of the contents was Times New Roman, and the font size was 12. The line spacing between each line of the paragraphs was 1.5.

During paper-based and computer-based reading tasks, subjects were asked to determine the number of occurrences of certain letters (t, T, f and F) in the paragraphs. For computer-based tasks, the subjects were asked to read paragraphs on a 19-inch computer screen, and to indicate on the provided paper whenever they found the letters t, T, f and F. The subjects were allowed to control the brightness and contrast settings according to their preferences so that they did not have any visual discomfort from the computer screen. For the paper-based task, the subjects were asked to read paragraphs printed on standard letter-sized white paper used for general office documents. They were asked to mark these letters with the paragraphs.

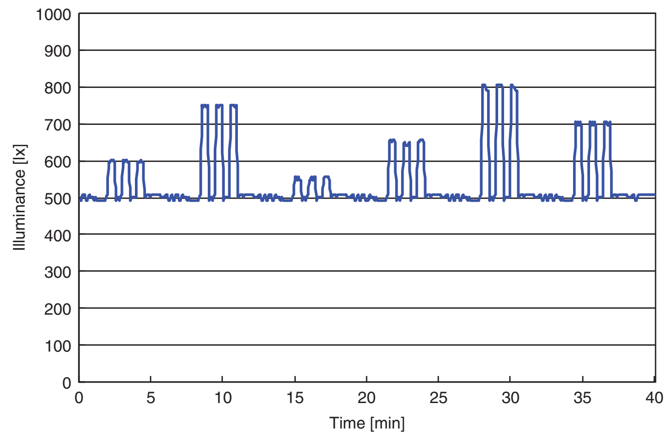

Fig. 2. Illuminance fluctuation pattern at 500 lx base level.

Table 2. Rating scale for answer

Answer	Rating scale
Strongly Agree	3
Moderately Agree	2
Slightly Agree	1
Neither Agree nor Disagree	0
Slightly Disagree	−1
Moderately Disagree	−2
Strongly Disagree	−3

Once the annoyance test performed under each base level condition was completed, the subjects were asked to answer for the questionnaires using the rating scale listed in Table 2. The rating scale was integer and the subjects had to decide whether their answer should fall into each integer. The answer from the subjects were collected and input into a spread sheet program for statistical analysis.

Photometric sensors manufactured by *L* company were used to monitor illuminance. They detected illuminance in currents and converted into standard units using assigned calibration constants. The sensitiveness of the photometric sensors was typically 20 mA/100 klx, and the maximum deviation of linearity was 1% up to 100 klx [11]. An automatically equipped data monitoring system manufactured by *C* company was used for data recording. The main data logging system contained 37 differential channels, and its accuracy ranged from −2.5 mV to

2.5 mV for temperatures between 0°C and 40°C [12]. The illuminance levels at 15 points in the full-scale mock-up space were monitored at intervals of 10 s during the entire survey period.

Results

General Characteristics of Subjects

Nineteen female and 17 male graduate and undergraduate students who have experience of using computers participated in the annoyance tests set up in this study. Their ages ranged from 20 to 45, and the mean age was 29. A detailed distribution of the subjects' ages is summarised in Table 3. Overall, 69.4% of the subjects were younger than 30, and 27.8% were between 31 and 40. One subject was older than 40.

Seventeen subjects had normal vision without wearing glasses or contact lenses. Sixteen subjects wore glasses, and 3 subjects used contact lenses. With the vision aids, all subjects had normal vision and had no problems in performing typical office tasks such as paper-based and computer-based reading tasks. None of the subjects was colour blind. The subjects' visual sensitivities to glare and colour from light sources are summarised in Figure 3. Overall, 77.8% of the subjects were sensitive to glare generated by the light (M = 1.25, SD = 1.40). About 75.1% of the subjects reported that they were sensitive to the colour projected from light sources.

Table 3. Subject's age

Range	Frequency	Percentage	Statistics
20–25	13	36.1	Mean: 29
26–30	12	33.3	Min.: 20
31–35	5	13.9	Max.: 45
36–40	5	13.9	
>40	1	2.8	
Total	36	100	

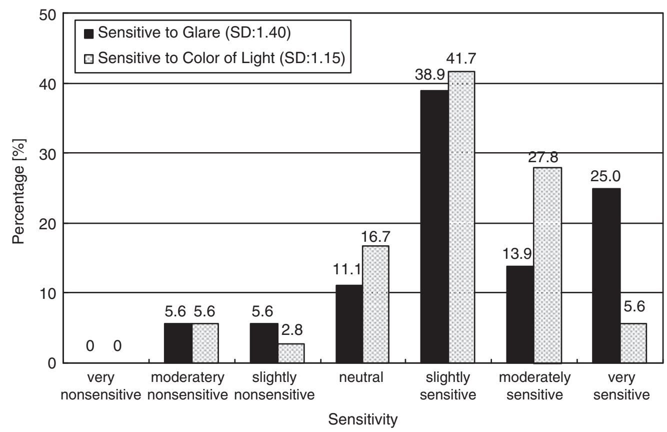

Fig. 3. Subjects' visual sensitivity.

Visual Perception Under Constant Illuminance

The dimming control system was initially set up to maintain two constant illuminance levels of 500 lx and 650 lx on the desktop for the paper-based and computer-based reading tasks, respectively. While the desktop illuminance was kept constant within certain ranges, the illuminance on indoor surfaces showed its own variation ranges. The illuminance levels on the surfaces of the full-scale mock-up space under two constant illuminance conditions are shown in Figures 4 and 5.

For the 500 lx condition, the desktop illuminance ranged from 493 lx to 509 lx during the monitoring period. The variation range was 16 lx, which was 3.14% of the maximum illuminance on the desktop. The mean illuminance levels on the north and east walls varied from 210 lx to 261 lx and from 220 lx to 271 lx, respectively. The illuminance on the computer screen ranged from 171 lx to 194 lx. The illuminance level at the position of subjects' eyes varied from 119 lx to 135 lx.

When the desktop illuminance was maintained at 650 lx, the desktop illuminance ranged from 642 lx to 658 lx, and the illuminance on the north wall varied from 261 lx to 320 lx. The illuminance on the east wall varied from 275 lx to 341 lx. The illuminance at the position of subjects' eyes ranged from 151 lx to 207 lx, and the illuminance on the computer screen varied from 218 lx to 241 lx.

Evaluation of Visual Environment

Overall, the mean responses to the visual environment under two constant desktop illuminance conditions showed differences within acceptable ranges except for two cases. The mean responses under the constant illuminance conditions are summarised in Table 4. The feeling that the light was well distributed (A1) increased as the desktop illuminance changed from 500 lx to 650 lx. Their mean responses increased from 0.92 to 1.53 on the rating scale. This result means that the increase of background illuminance could potentially influence the visual sensation of the subjects.

The two base level illuminance conditions did not cause any strong glare that bothered the subjects performing computer-based reading tasks (A2) or paper-based reading tasks (A3). Overall, the mean rating for computer-based tasks was slightly greater, since there

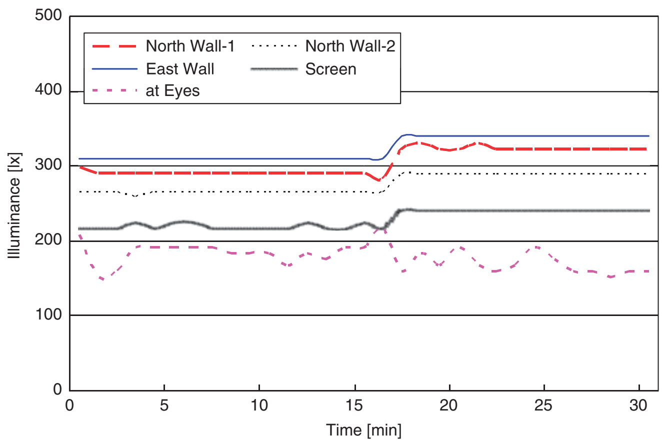

Fig. 4. Illuminance variation (constant 500 lx condition).

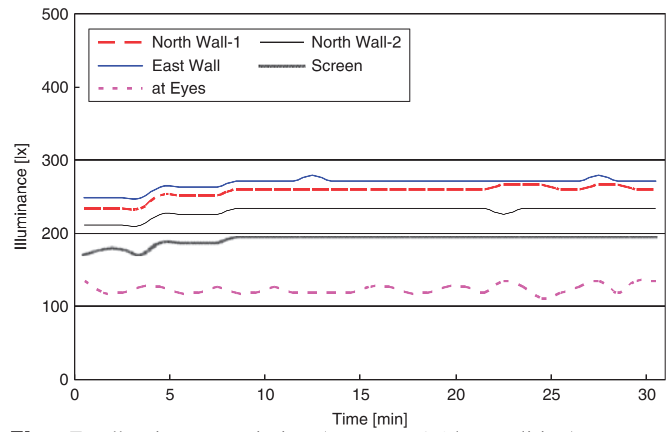

Fig. 5. Illuminance variation (constant 650 lx condition).

Table 4. Mean responses of visual annoyance under constant illuminance conditions

Question number	500 lx constant illuminance		650 lx constant illuminance	
	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)
A1	0.92	1.6	1.53	1.44
A2	−0.78	1.73	−1.06	1.74
A3	−0.81	1.75	−1.19	1.75
A4	−0.06	1.26	0.47	1.30
A5	−0.36	1.40	0.50	1.21
A6	−0.08	1.50	0.75	1.68
A7	0.53	1.23	0.33	1.26

was luminous projection from the computer screen toward subjects' eyes. The glare that bothered the subjects during reading tasks decreased slightly as the illuminance was increased from 500 lx to 650 lx. This implies that the background illuminance should be greater than 500 lx to avoid potential visual annoyance in the space.

The 500 lx conditions were neither too dim nor too bright for the computer-based reading tasks (A4). As the illuminance was increased to 650 lx, the subjects began to feel that it was slightly too bright, but it was almost within the neutral range on the rating scale. However, the 500 lx condition was considered slightly dim for the paper task (A5). This result implies that changes of lighting under this condition can effectively influence visual perception, because the background illuminance was considered to be slightly dim for the tasks. No significant difference was detected between the mean responses for computer-based and paper-based reading tasks.

The subjects replied that the 650 lx illuminance condition was favourable for computer (A4) and paper tasks (A5), although they did not show a significant difference between the two tasks, respectively. These mean ratings increased by 0.53 and 0.86 on the rating scale, respectively, compared with those under the 500 lx condition. Those results were directly linked to the mean response regarding visual satisfaction with the light condition (A6). The increase of illuminance enhanced the mean vote by 0.83 on the rating scale compared with that under the 500 lx condition. Under the 500 lx condition, the subjects were not satisfied with the overall visual environment in the space. This result implies that the illuminance level should be greater than 500 lx to improve the visual satisfaction of occupants.

These findings were significantly linked with the mean vote to increase the illuminance level to achieve a greater visual satisfaction for the computer-based and paper-based reading tasks. The subjects preferred more light for visual satisfaction. Overall, the subjects expressed a slight desire to increase the illuminance level under the 500 lx condition (A7). Although the 650 lx illuminance condition satisfied the subjects, there was still a slight need to increase the illuminance level.

In summary, the two constant illuminance levels in this study did not cause significant glare for computer-based and paper-based reading tasks. The glare sensation under the 500 lx condition did not differ between computer and paper tasks. However, the glare sensation was slightly greater for the computer-based task performed under the 650 lx condition due to the lighting from the computer screen and the increased light output from the lighting fixture. This implies that the increase of background illuminance is a potential factor that should be considered in the analysis of visual perception. As long as the subjects did not feel any visual annoyance, they would prefer to have a higher illuminance level to satisfy their visual needs for the reading tasks.

Mean Responses of Visual Threshold and Mood

The mean responses of mood and visual thresholds that influence visual perception differed under the two constant illuminance conditions. The mean responses are summarised in Table 5. The mood for the visual environments (M1–M5) increased as the desktop illuminance changed from 500 lx to 650 lx. The increased mean votes for the feeling ranged from 0.03 to 0.69 on the rating scale.

However, the two base level illuminance conditions did not successfully improve the moods of subjects. This means that the illuminance was not the only factor that influenced mood, although the higher illuminance conditions could improve the mean votes of mood perception slightly. Among all mood responses, the feeling of being fidgety was not perceived as the base level illuminance increased (M5).

The mean votes pertaining to perception of visual thresholds (M6–M9) ranged from −0.03 to 0.67 on the voting scale. Overall, the subjects were less irritated visually with an increase in illuminance. The mean votes were higher than the neutral point under 500 lx conditions, and improved as the illuminance was increased from 500 lx to 650 lx. In particular, the increase of illuminance effectively influenced the sensation of seeing the letters clearly.

The subjects felt that the visual environment was clear enough to see the letters on the paper and computer screen (M8). The mean votes exceeded the neutral point on the rating scale, but that does not mean that the subjects perceived no visual stimulating factors under the two illuminance conditions, because the mean votes for the other three visual perceptions (M6, M7, M9) were lower than 1 on the rating scale.

In summary, the subjects preferred the 650 lx condition in terms of visual perception due to the increased illuminance. The two constant lighting conditions did not cause any significant visual irritation, but the 500 lx condition showed a neutral response on the rating scale. Mood responses (M1–M5) improved as the desktop illuminance increased. As the illuminance became 650 lx, the mean votes started to exceed the neutral point on the rating scale. Under the two illuminance conditions, changes of lighting did not lead to significant differences regarding temporary feelings about eye fatigue, visual distraction, difficulty in seeing, or visual stimulation (M6–M9).

Responses under Fluctuating Illuminance Conditions

Visual Responses and Annoyance

The mean responses of visual annoyance differed according to the ranges of illuminance under the two base level conditions. The mean responses of visual perception including annoyance, satisfaction, and preference are shown in Figures 6 to 9. Overall, the results indicate that the subjects became more annoyed with an increasing fluctuation of illuminance under the two base level conditions.

Table 5. Mean responses of mood and visual thresholds under constant illuminance condition

Question number	500 lx constant illuminance		650 lx constant illuminance	
	Mean (M)	Standard deviation (SD)	Mean (M)	Standard deviation (SD)
M1	−0.36	1.61	0.39	1.59
M2	−0.33	1.59	0.36	1.57
M3	0.28	1.47	0.31	1.43
M4	−0.86	1.46	−0.17	1.68
M5	0.86	1.51	1.08	1.57
M6	−0.03	1.42	0.67	1.66
M7	0.08	1.30	0.42	1.52
M8	0.67	1.66	1.22	1.66
M9	0.22	1.66	0.44	1.27

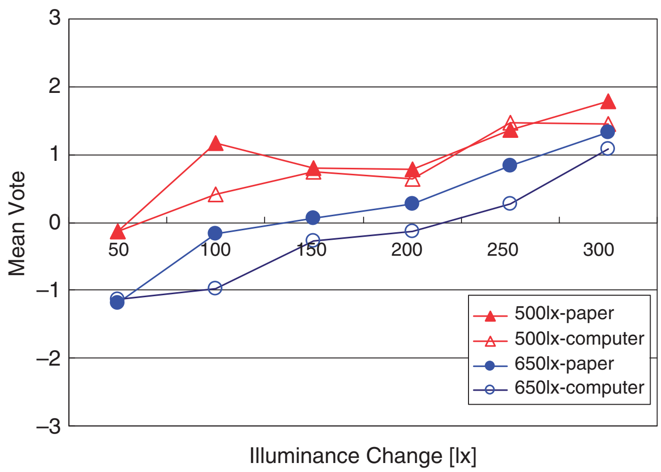

Fig. 6. Mean responses for overall visual annoyance.

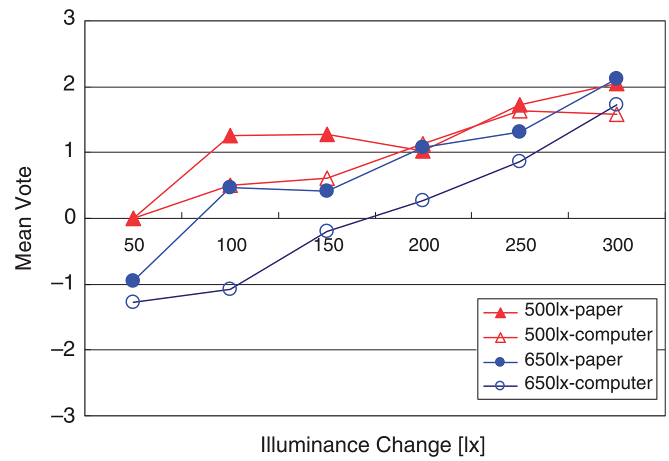

Fig. 8. Mean response for visual sensitiveness to changes of illuminance.

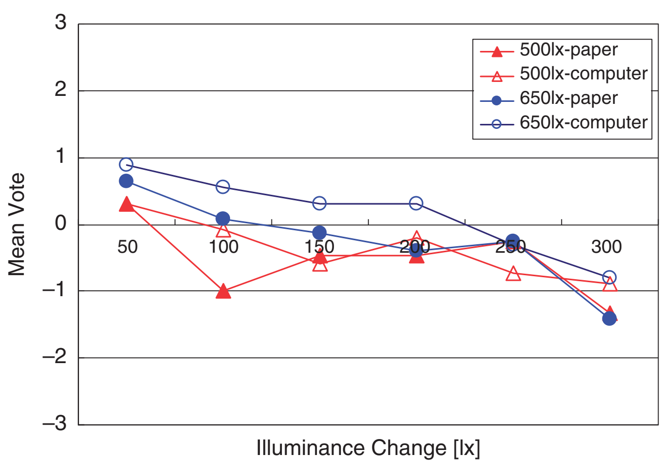

Fig. 7. Mean response for visual satisfaction.

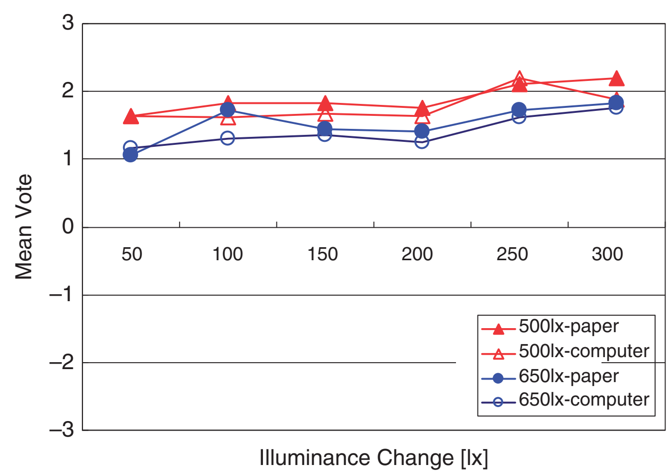

Fig. 9. Mean response for preference to keep constant lighting.

Equal amounts of illuminance fluctuation were shown to have influenced visual annoyance differently under the two base level conditions. Annoyance under the 500 lx base level condition was worse than that under the 650 lx base level condition. The subjects were slightly less bothered by the change of light when they performed computer-based reading tasks compared to paper-based tasks. These results agree with the research hypothesis of this study that the background illuminance level is critical to annoyance perception, and that it can be further reduced under higher illuminance conditions.

As shown in Figure 6, the mean responses of overall visual annoyance (FA1) for the paper-based and computer-based reading tasks increased as the illuminance was increased under the two base level conditions. They showed distinct differences under different base level conditions. The subjects were more seriously annoyed by the changes of illuminance under the 500 lx base level conditions than under the 650 lx base level conditions.

For paper tasks under the 500 lx base level, the overall annoyance (FA1) was not very significant until the change in illuminance became 250 lx (M = 1.36, SD = 1.20). Below this level and until the illuminance was changed up to 200 lx, the subjects were slightly annoyed by the changes in illuminance (M = 0.78, SD = 1.44). On the contrary, under the 650 lx base level condition, the overall annoyance was not very significant until the change of illuminance became 300 lx (M = 1.33, SD = 1.66). Below this change level, the subjects were not significantly annoyed by the changes until the illuminance reached 250 lx (M = 0.83, SD = 1.36).

In general, the subjects were slightly less bothered by the change in illuminance when they performed computer-based tasks. The overall annoyance under the 500 lx base level conditions was not significant until the change of illuminance became 250 lx (M = 1.47, SD = 1.06). Under the 650 lx base level, the overall annoyance was not significant until the illuminance change became 300 lx (M = 1.08, SD = 1.42). For all cases where the illuminance changes were less than 250 lx, the subjects did not feel annoyance due to the change of illuminance. This result means that the maximum fluctuation range of illuminance that does not cause significant annoyance for computer-based reading tasks was 200 lx and 250 lx for the 500 lx base level and 650 lx base level conditions, respectively.

The responses pertaining to visual satisfaction (FA2) shown in Figure 7, decreased significantly as the change of illuminance was increased. The visual satisfaction for paper-based and computer-based tasks became different when the change reached 100 lx under the 500 lx and 650 lx base level conditions. The subjects were less satisfied with the illuminance when they performed paper-based tasks. The response for visual satisfaction was different according to the base level conditions. As the illuminance change became higher, the subjects became less satisfied under the 500 lx base level than the 650 lx base level conditions. The equal amount of illuminance change had caused less dissatisfaction under 650 lx base level conditions.

For paper-based tasks under 500 lx base level conditions, subjects were not visually satisfied (FA2) when the range of illuminance became 300 lx (M = −1.33, SD = 1.33). Below this range, e.g. when the change was 250 lx, the subjects did not feel strongly dissatisfied nor satisfied (M = −0.25, SD = 1.71). The mean response in visual satisfaction under 650 lx base levels showed a similar pattern to that of the annoyance feeling. The subjects expressed a slight dissatisfaction when the illuminance change was 200 lx (M = −0.39, SD = 1.40), and they were dissatisfied when the change reached 300 lx (M = −1.42, SD = 1.50).

When computer-based tasks were performed under the 500 lx base level conditions, the visual satisfaction (FA2) for the illuminance change differed slightly from that of the paper-based tasks. For all six change ranges, the subjects were satisfied to some degree, but this was not significant when the change range of illuminance was 300 lx (M = −0.89, SD = 1.19). For the 250 lx change conditions under the 650 lx base level, the subjects were dissatisfied to an insignificant degree (M = −0.31, SD = 1.49). When a 300 lx change happened, the subjects were slightly unsatisfied (M = −0.81, SD = 1.37), and this result differed from that of the paper-based task (M = −1.42, SD = 1.50). The result appears to occur since light projected from computer screens toward subjects' eyes mitigates a perceived change in background illuminance.

The feeling of visual sensitiveness to the change in illuminance (FA3) as shown in Fig. 8 was greater under the 500 lx base level condition. This implies that an equal amount of illuminance change can cause different visual sensations under different target illuminance. This might be the reason for the different responses regarding visual annoyance and satisfaction under the two different base level conditions.

For the paper-based task under the 500 lx base level, the subjects sensitively responded to all changes in illuminance from 100 lx to 300 lx. However, their sensitiveness was near the neutral point for the change levels below 200 lx under the 650 lx base level condition (M = 0.42, SD = 1.83), and they were observed to be not sensitive to the illuminance change of 50 lx (M = −0.94, SD = 1.64).

Compared to the paper-based task, subjects were relatively insensitive to change of lighting when computer tasks were performed. They became sensitive to changes in lighting when the changes began to exceed 200 lx. The subjects responded that they became highly sensitive to the changes of lighting when the changes was 300 lx (M = 1.72, SD = 0.97) under the 650 lx base level. The change of 250 lx was not considered significant (M = 0.86, SD = 1.68), which means that the change of 250 lx was acceptable in terms of visual sensitiveness to illuminance fluctuation. The subjects were less sensitive to the same changes of illuminance compared to the paper-based task. It appears that the luminance and bright computer screen had contributed to this result.

As shown in Figure 9, the subjects did not prefer changing illuminance (FA4), although they did not show significant annoyance or visual discomfort for particular change levels under the two base level conditions. The subjects' discomfort to the changing illuminance under the 500 lx base level condition was stronger than that for the 650 lx base level condition. This result likely occurred because the subjects already noticed that the lighting conditions would be changed, although the instructions before the survey did not offer any clues about the upcoming changes in illuminance.

For paper-based tasks under the two base levels conditions, the subjects did not prefer fluctuating lighting. They preferred a constant lighting condition (M = 1.64, SD = 1.27), and their preference to have constant lighting decreased as the base level illuminance increased to 650 lx (M = 1.06, SD = 1.57).

For the computer-based task, the subjects again did not prefer fluctuating lighting, although the responses were generally slightly lower than those for the paper-based task. Under the 500 lx base level, the subjects became annoyed when the illuminance fluctuation was greater than 250 lx. This implies that the maximum fluctuation range of lighting for the computer-based task was 200 lx in order to avoid annoying the subjects (M = 0.39, SD = 1.73). Under the 650 lx base level, the subjects did not want to have fluctuating lighting (M = 1.25, SD = 1.38), although their response was neutral for changes of less than 200 lx (M = 0.31, SD = 1.31).

Predictive Models for Visual Sensitiveness to Illuminance Change

Linear regression models were developed to predict the subjects' responses of visual sensitiveness to changes of illuminance when paper-based and computer-based tasks were performed under the two base level conditions. The mean response of visual sensitiveness to illuminance change was considered a dependent variable, and the variation in desktop illuminance was considered an independent variable. The relationship between them is shown in Figures 10 and 11. Each data point on the graph represents the mean response of annoyance from the 36 subjects when they performed paper-based and computer-based reading tasks.

Overall, all prediction models for the two base levels indicated that an acceptable linear relationship existed between the changes in illuminance and mean votes of sensitiveness to that change, since the ANOVA results shown in Table 6 illustrate that the significance level was lower than 0.05 for all reading tasks under the two different base level conditions. In addition, the linear correlation between them was strong, since the coefficient of determination ranged from 0.7515 to 0.9805. This means that the reduced variation in mean responses of visual sensitiveness to illuminance changes were from 75.15% to 98.05% for each given reading task under different base level conditions.

The linear analysis implies that the subjects were less bothered by the changes in lighting when they performed computer-based reading tasks than for paper-based reading tasks. This means that a greater fluctuation range of illuminance is acceptable for computer-based reading tasks in a small office when the lighting system is

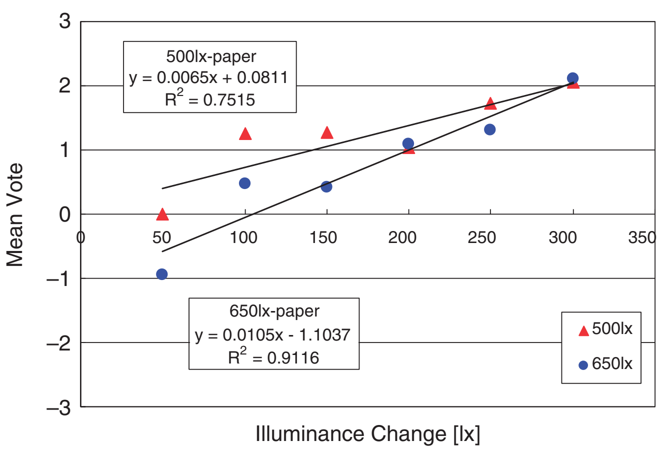

Fig. 10. Relationship between illuminance fluctuation and visual sensitiveness to changes in lighting (paper-based reading task).

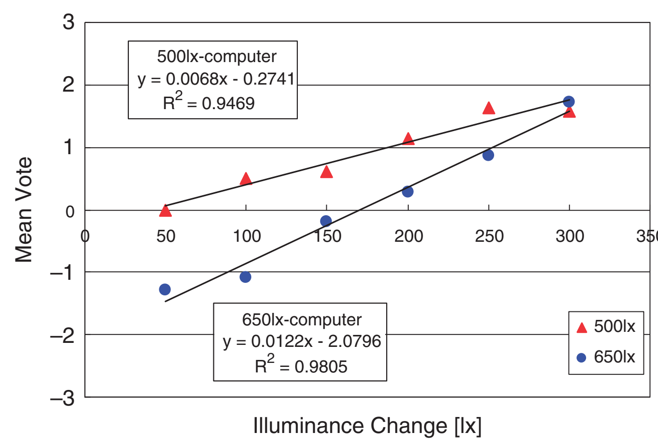

Fig. 11. Relationship between illuminance fluctuation and visual sensitiveness to changes in lighting (computer-based reading task).

Table 6. Linear relationship between visual sensitiveness and illuminance fluctuation

Task type	Base level illuminance	Variable	Unstandardised coefficient		*t*	Sig.	ANOVA	
			B	Standard error (SE)			'*F*' test	Sig.
Paper	500 lx	Constant	0.0811	0.37	0.22	0.83	*F*(1,4) = 12.06	0.03
		Change	0.0065	0.00	3.47	0.03		
	650 lx	Constant	−1.1037	0.32	−3.48	0.03	*F*(1,4) = 41.95	0.00
		Change	0.0105	0.00	6.48	0.00		
Computer	500 lx	Constant	−0.2741	0.16	−1.73	0.16	*F*(1,4) = 69.87	0.00
		Change	0.0068	0.00	8.36	0.00		
	650 lx	Constant	−2.0796	0.17	−12.57	0.00	*F*(1,4) = 205.43	0.00
		Change	0.0122	0.00	14.33	0.00		

controlled by a dimming system that control electric lighting output instantaneously. According to the regression model, the acceptable ranges of illuminance change that did not cause any negative visual influence under 500 lx base level conditions were 141.3 lx for paper-based reading tasks and 200.3 lx for computer-based reading tasks. For the base level illuminance of 650 lx, the acceptable ranges were 200.3 lx and 252. 4 lx for paper-based and computer-based reading tasks, respectively.

These results imply that the background illuminance that formed the overall visual environment in the space functioned as an important factor in the visual perception that occurred under the fluctuating illuminance. The higher background illuminance made the subjects react less to equal changes of lighting output. When computer tasks were performed, the fluctuation of illuminance was not perceived significantly by the subjects due to the lighting projected from the screen, which functioned as a barrier against visual annoyance caused by a change in illuminance. This result is meaningful to selecting target illuminance levels for office spaces when dimming control systems are applied.

Perceptions of Mood and Visual Thresholds

The mean responses regarding mood and the perception of visual thresholds varied as the illuminance fluctuated under the two base level conditions. The mean responses for those factors are shown in Figures 12 to 15.

Overall, the mood responses and perception of visual thresholds improved as the desktop illuminance increased. As the illuminance became 650 lx, the responses began to exceed the neutral point on the rating scale. The 650 lx condition was preferred for a better mood, but a significant difference was not always detected between the responses for 500 lx and 650 lx conditions. These responses did not show a wide range of changes as the illuminance increased under the two base level conditions.

The mood (M1–M5) and visual perception for thresholds (M6–M9) under fluctuation illuminance became worse than those under the constant illuminance condition. When the illuminance change was 50 lx, responses such as like (M1), pleasant (M2), relaxed (M3) and attractive (M4) improved slightly, but the improvement was not significant. However, the subjects' moods became worsen as the change in illuminance increased beyond 50 lx, which was an exceptional case that slightly improved the mood.

The mean votes of responses for computer-based reading tasks were slightly improved compared to the

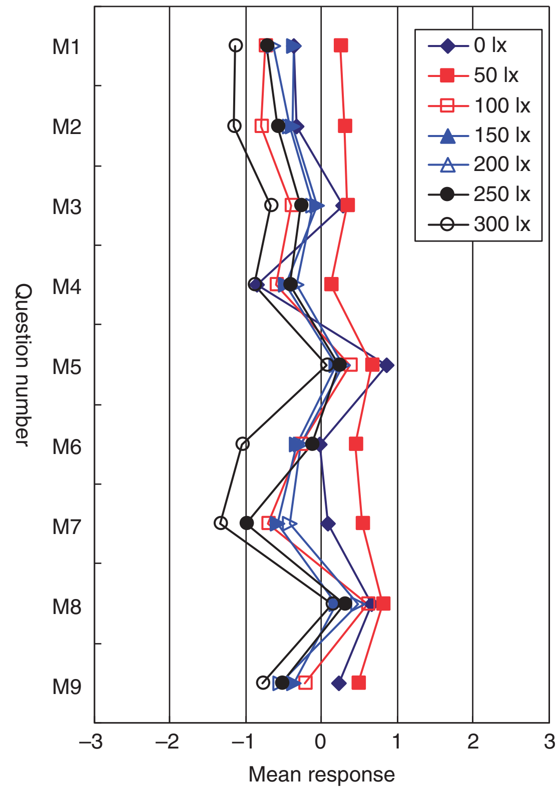

Fig. 12. Mean response of mood and visual perception for illuminance fluctuation (paper-based reading task, 500 lx base level).

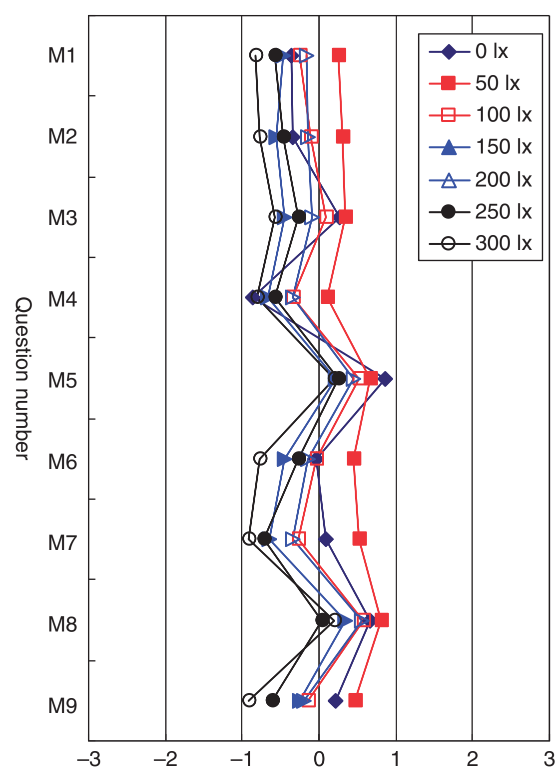

Fig. 13. Mean response of mood and visual perception for illuminance fluctuation (computer-based reading task, 500 lx base level).

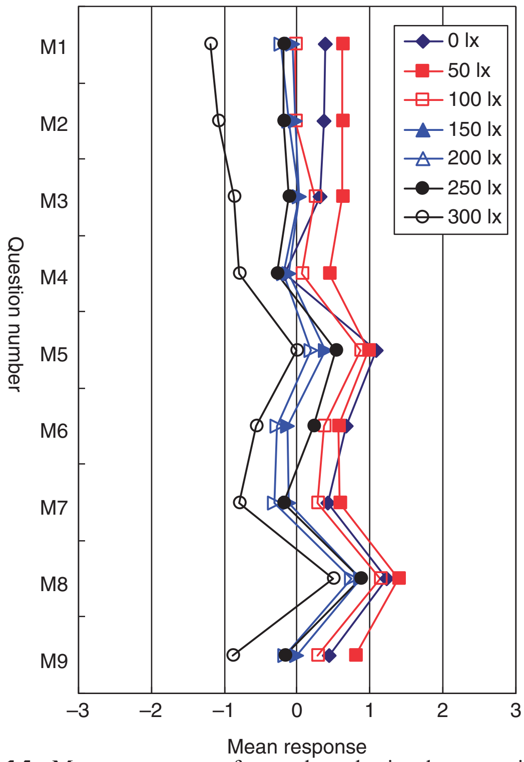

Fig. 14. Mean response of mood and visual perception for illuminance fluctuation (paper-based reading task, 650 lx base level).

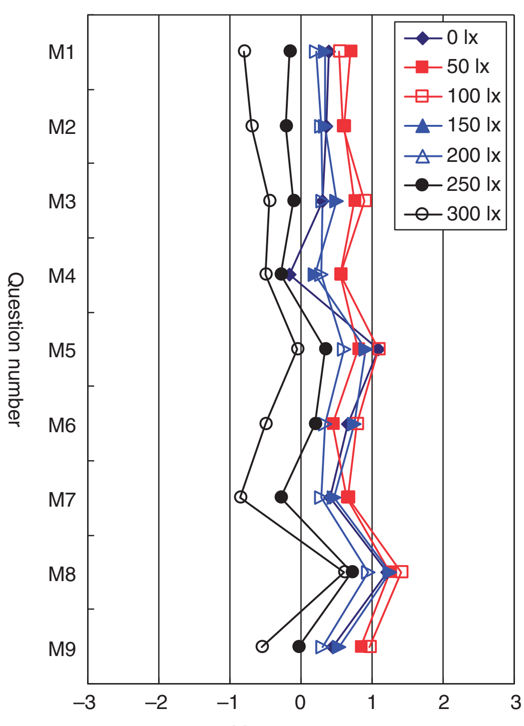

Fig. 15. Mean response of mood and visual perception for illuminance fluctuation (computer-based reading task, 650 lx base level).

paper-based task, due to the light projected from the computer screen. This result appeared to occur because the subjects did not perceive the change in illuminance due to the luminous projection from the screen, which covered some of the viewing angles of their eyes. These results are consistent with the research hypothesis set up in this study. The change in the range of mood feelings for the computer task was slightly narrower than for the paper task when the illuminance levels changed.

On the contrary, the illuminance change impaired their mean responses for paper tasks, because the illuminance changes were perceived by the subjects due to the lack of an additional light source in front of their eyes. This also occurred for the 500 lx and 650 lx base level conditions and implies that the additional luminous projection toward subjects' eyes from computer screens mitigated their visual perceptions of illuminance change.

Under the two different base level conditions, the illuminance change did not cause significant differences for temporary feelings about eye fatigue (M6), visual distraction (M7), difficulty seeing letters (M8) or visual stimulation (M9). Similar to the annoyance feeling (FA1), the influence of equal amounts of lighting fluctuation on mood responses was not identical for the two base level conditions. When the 500 lx base level illuminance conditions were maintained, the mean votes declined for the perception of visual thresholds. On the contrary, the higher background lighting conditions mitigated the visual perception of the illuminance change in the space, and resulted in improved mean votes. This is consistent with the research hypothesis discussed in this study.

In summary, the responses for visual thresholds worsened as the lighting fluctuation increased, which differed according to the base level conditions. Although no significant visual annoyance was reported under slightly fluctuating illuminance, fluctuating illuminance conditions were not strongly preferred by the subjects, because the changes would cause visual thresholds that annoyed the subjects.

Relationship between Visual Annoyance and Mood

The multiple linear regression method was used to predict the visual annoyance level affected by visual stimulating factors caused by the changes in illuminance. The response of overall visual annoyance (FA1) was considered as a dependent variable. The stimulating factors of visual annoyance such as eye fatigue (M6), visual distraction (M7), difficulty seeing letters (M8), visual stimulation (M9), and visual sensitiveness to

Table 7. Multiple linear regression analysis for visual annoyance (paper-based reading task)

Factor	500 lx base level				650 lx base level			
	Unstandardised coefficient		t	Sig.	Unstandardised coefficient		t	Sig.
	B	Standard error (SE)			B	Standard error (SE)		
Constant	0.161	0.09	1.79	0.07	−0.177	0.09	−1.89	0.06
Sensitive to light	0.431	0.06	7.79	0.00	0.457	0.05	8.41	0.00
Visual distraction	−0.465	0.06	−8.45	0.00	−0.258	0.08	−3.15	0.00
Visual stimulation	**	**	**	**	−0.194	0.08	−2.29	0.02
ANOVA test	$r^2 = 0.5596$, $F(2,210) = 135.31$, Sig. = 0.00				$r^2 = 0.4841$, $F(3,210) = 66.30$, Sig. = 0.00			

**Variables not selected in the regression models.

Table 8. Multiple linear regression analysis for visual annoyance (computer-based reading task)

Factor	500 lx base level				650 lx base level			
	Unstandardised coefficient		t	Sig.	Unstandardised coefficient		t	Sig.
	B	Standard error (SE)			B	Standard error (SE)		
Constant	0.136	0.08	1.77	0.08	0.057	0.10	0.55	0.58
Sensitive to light	0.510	0.05	10.42	0.00	0.326	0.05	6.58	0.00
Visual distraction	−0.415	0.05	−7.66	0.00	−0.279	0.08	−3.67	0.00
Difficult to see	**	**	**	**	−0.148	0.07	−2.08	0.04
Visual stimulation	**	**	**	**	−0.212	0.08	−2.65	0.01
ANOVA test	$r^2 = 0.5979$, $F(2,210) = 158.38$, Sig. = 0.00				$r^2 = 0.5242$, $F(4,210) = 58.11$, Sig. = 0.00			

**Variables not selected in the regression models.

illuminance change (FA3) were considered independent variables.

The five factors were used in initial models, and their contributions to the predictive models were tested using the significance level of 0.05. The independent variables that were acceptable under the significance level were included in the final prediction model. The final models were tested to investigate whether the linear relationships between them were meaningful. The results are shown in Tables 7 and 8.

Overall, the prediction models for 500 lx and 650 lx indicated that an acceptable linear relationship existed between annoyance and stimulating factors included in the models; because the ANOVA test results showed that the significance level was lower than 0.05. The coefficients of determination for the models ranged from 0.4841 to 0.5979. This indicates that the reduced error variation in mean responses for the visual annoyance ranged from 48.41% to 59.79% when the selected factors were considered to predict overall annoyance for both paper-based and computer-based reading tasks.

When paper-based tasks were performed under the 500 lx base level condition, visual sensitiveness, and visual distraction were strong contributors to the visual annoyance. Annoyance showed a reasonably linear correlation with these factors, and the correlation coefficient was 0.5596. The other three factors did not appear to influence the perception of visual annoyance. As the base level illuminance increased to 650 lx, the visual stimulation was found to be an important factor affecting visual annoyance in addition to the two factors considered under the 500 lx base level conditions. This implies that visual sensitiveness to the change of lighting; feelings of visual distraction, and stimulation were significant factors that should be considered to lessen visual annoyance under fluctuating illuminance conditions.

Like the paper-based tasks, visual sensitiveness to the change of lighting and visual distraction could significantly influence visual annoyance when the computer-based task was performed under the 500 lx base level condition. Their significance levels were less than 0.01, which means that these two feelings were significant factors contributing to visual annoyance when computer tasks were performed. Visual stimulation and difficulty seeing a letter on screen were meaningful contributors to the perception of visual annoyance under the 650 lx base level conditions.

It appears that luminance and brightness from the computer screen can function as another light source that contributed to the visual annoyance. Accordingly, the subjects had difficulty seeing the letters on the computer screen, which resulted in visual annoyance. Under this condition, the visual annoyance was influenced by those factors that stimulated the eyes. The four prediction models imply that feelings of visual sensitiveness to the changes in lighting and visual distraction were common factors that had influenced the perception of visual annoyance under the two base level conditions. In particularly, visual distraction functioned significantly under the 500 lx base level conditions, and visual stimulation was also a meaningful contributor under 650 lx base level conditions.

Conclusion and Future Work

Field measurements and visual annoyance tests were performed in a full-scale mock-up office space to analyse the effects of fluctuating illuminance on visual perception and mood. The following is a summary of findings from this study.

1. In general, subjects were more annoyed visually as the fluctuation range of illuminance increased when computer-based and paper-based reading tasks were performed. Equal amounts of illuminance fluctuation could influence visual annoyance differently under 500 lx and 650 lx base level conditions. The annoyance under the 500 lx base level condition was worse than that under the 650 lx base level condition. This implies that the background illuminance level was critical to the annoyance perception, and the annoyance can be further reduced under higher illuminance task level conditions.
2. The subjects were less bothered by changes in lighting when they performed computer-based reading tasks than paper-based reading tasks. In addition, a greater satisfaction was reported when computer tasks were performed. This indicates that a greater fluctuation range of illuminance is acceptable for computer-based reading tasks in a small office when the lighting system is controlled by a dimming system. In this study, the acceptable ranges of illuminance changes under 500 lx base level conditions were 141.3 lx for paper-based reading tasks and 187.3 lx for computer-based reading tasks. As the base level illuminance increased to 650 lx, the acceptable ranges were 200.3 lx and 252.4 lx for paper-based and computer-based reading tasks, respectively.
3. The increase in task illuminance improved the mood in the room. The mean responses on mood under the 650 lx task illuminance condition showed higher ratings toward better mood than under the 500 lx condition. The influence of equal amounts of lighting fluctuation on mood responses was not identical for the two base level conditions. The responses under the 650 lx base level condition showed better mood compared to those under the 500 lx base level conditions. However, these responses did not show a wide range of changes as the lighting was increased under the two base level conditions.
4. Multiple linear prediction models indicated that feelings of visual sensitiveness to the changes in lighting, visual distraction, and stimulation were significant contributors to overall visual annoyance under fluctuating lighting conditions. This implies that lighting systems controlled by a dimming system should not cause visual distraction to improve occupants' visual satisfaction for office activities.

The mock-up space was furnished like a real office space, but it did not have all the environmental features that would be found in a real office space. This could have an influence on the annoyance and psychological responses of the subjects. It would be useful in future work to perform the test in a real office space where daylight is available in order to reduce the effects of uncertainty for the habitation. The results of this research are entirely based on responses from 36 student subjects. Responses from a larger number of subjects selected among more diverse samples would be helpful to achieve more reliable results that would better represent the general population of office occupants.

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