Paper

Perception of Lighting Fluctuation in Office Lighting Environment

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ABSTRACT

The non-periodic fluctuation of artificial lighting in offices was investigated to clarify the threshold at which the fluctuation is perceived. The experiments showed that fluctuation ratio of 0.92-1.06, i.e. 7% of the fluctuation, is not perceived when the observers tried to be conscious of the fluctuation. On the other hand, under the condition of being unconscious of the fluctuation because of assigned visual tasks, the threshold has a broader range (0.8-1.3) and the value rises with the fluctuation period. It is important to dim artificial lighting without causing discomfort to office workers, and the results of this study can be used to better control, fluctuation in office lighting.

KEYWORDS: lighting fluctuation, lighting control, fluctuation in illuminance, office lighting

1. Introduction

From a global environmental perspective, energy saving is one of the most important requirements for the lighting equipments in buildings today, also more efficient hardware for that lighting is demanded.

In addition to the hardware, technological developments on software, and energy saving methods for the operation of the hardware are proceeding rapidly. One example, mainly applied to office lighting, is a self-controlled system¹⁾. This system possesses a function that keeps the desk-illuminance constant by sensing the intensity of light reflected from the environment and controlling light emission of the luminaire. When a room has a good amount of ambient light where normally actual illuminance exceeds the required illuminance, energy saving can be achieved through light sensing methods by reducing light output when lighting equipment is newly installed. In short, energy saving can be achieved by minimizing or maximizing light output of artificial illumination to maintain desired illuminance.

Under such lighting environments, daylight and light from artificial lighting fluctuate with time. This fluctuation is perceived as brightness fluctuation. Fluctuation is perceived when it exceeds a certain level. However, the situation and behavior of the person in the room may affect recognition and evaluation of the fluctuation, such as, whether one perceives the fluctuation, whether one can accept the fluctuation, and whether one feels uncomfortable with the fluctuation. Assuming that this method is applied to office lighting, uncomfortableness can be prevented if artificial lighting is controlled and the fluctuation is not perceived. To this end, this study has focused on the perception of lighting fluctuation in an office environment

Previous studies on lighting fluctuation examined perception of flicker using periodic fluctuation of lighting,

which is a classical issue of perception. Kelly²⁾ examined the amplitude threshold of flicker for a stimulus that was modulated with a temporal sinusoidal function and found that the maximum flicker sensitivity lies in the frequencies between 5 and 20 Hz. In Japan, perception of the fluctuation was determined as voltage flicker, and ΔV_{10} was determined as an index of evaluating the flicker for a periodic voltage fluctuation. The fluctuation sensitivity function was standardized³⁾ by conducting a similar experiment to that of Kelly's.

The above studies examined flicker perception for a periodic fluctuation, assuming situations in which the alternation of light and dark repeated in a relatively short cycle. However, when we fluctuate lighting in order to control office lighting, the change is a non-periodic fluctuation from a light level A to a light level B without returning to level A. As for lighting changes in a lighting environment from A to B in a non-periodic manner for a given time, we can distinguish two types of change: the change to lighter (referred to as increasing light) and the change to dimmer (referred to as decreasing light). In the present study, we examined the perception of fluctuation for increasing light and decreasing light separately.

As for the factors that determine perception of lighting change, we can assume the amount of fluctuation (the amplitude of fluctuation in the studies mentioned above), the speed of change (the frequency in the studies mentioned above), and the adaptation level, based on the previous studies mentioned above. The lighting fluctuation in our discussion always appears as noise for office workers. In a real office environment, the degree of concentration on work related tasks may influence perception of lighting fluctuation in office workers. That is, the nature of the work is an important factor that affects perceptions of lighting

Fig.1 Experiment room.

changes, because it influences sensitivity to the those changes. This study attempted to clarify the perceptual characteristic with office workers engaging in several tasks for non-periodic lighting fluctuation.

2. Experiment 1: perception of a step change in illumination light

2.1 Experimental environment

The experimental room (Fig. 1) simulating an office room was approximately uniformly illuminated by 12 luminaires that have two Hf45W tubes, embedded in the ceiling (with white-painted louvers, shielding angle 30 deg). The openings of the room were shielded from outside light sources. The layout is shown in Fig. 2. These luminaire were controlled by a continuously dimmable ballast. The light-control signal was generated by a specially designed light-control signal generator that was connected to a personal computer, and was sent to each luminaire through the parallel port of the computer. By sending an 8-bit digital signal from the computer to the signal generator via the parallel port, we were able to control the lighting level with 256 steps.

Light measurement ensured that desk- illuminance (70 cm above the floor) in the center of the room changed in a linear fashion with 256 steps of the input signal, and that the maximum illuminance reached to about 1400 lx.

2.2 Stimulus for evaluation

In Experiment 1, we examined perceptual characteristics for the sharp change from the lighting status $E1$ to $E2$ as shown in Fig.3. To simulate the conditions of office work, the initial values of the illuminance on a desk was either 400 or 750lx, the ratio of the fluctuating illuminance ($E2/E1$) was varied from 0.79 to 1.21 with 23 steps. There were 46 stimuli prepared in total.

2.3 Methods

Each stimulus described above was presented at random as a lighting fluctuation pattern for approximately 10 seconds. The subject evaluated the lighting change using three alternatives of "changed", "unchanged", or "cannot determine".

Fig.2 Plan of experiment room.

Fig.3 Pattern diagram of fluctuation in illuminance used for Exp.1.

Fig. 4 Diagram of stimulus presentation process on Exp.1.

After the response, lighting returned to the initial level ($E1$) with an unnoticeable speed of change before the next trial (see Fig. 4).

Subjects were 14 males and 8 females (total 22), ages ranging from 20's to 60's. The number in the data set was 30, and some subjects repeated the measurement.

2.4 Results

Table 1 shows the evaluation values tallied for 23 stimuli with the initial illuminance of 750 lx. The rate of perception in the table was obtained by assigning 1 for "changed", 0.5 for "cannot determine", and 0 for "unchanged". These values were summed across the data set and divided by the number of useful responses. The rate of perception indicates the rate of subjects who perceived the fluctuation. By a similar procedure, the rate of perception was obtained for the condition of the initial illuminance of 400 lx. The results are plotted for each stimulus with the desk-illuminance after fluctuation for the abscissa, and the rate of perception for the ordinate (see Fig. 5).

We fit the data points in the figure by the normal cumulative distribution function (referred to as the normal c.d.f) for four conditions (increasing light and decreasing light from the two levels of initial illuminance) by using the maximum likelihood method. The curves are shown along

Fig.5 Desk-illuminance after fluctuation vs. its rate of the perception on Exp.1.

Table 1 Evaluation value and rate of perception on Exp.1: illuminance 750 lx.

No	Initial illuminance E_1	Illuminance after fluctuation E_2	Fluctuation ratio E_2/E_1	Number of subjects responded as follows			Rate of Perception (%)
				"changed"	"unchanged"	"cannot determine"	
1	750	596	0.79	30	0	0	100%
2	750	610	0.81	29	0	1	98%
3	750	624	0.83	29	1	0	97%
4	750	638	0.85	29	1	0	97%
5	750	652	0.87	25	3	2	87%
6	750	666	0.89	26	4	0	87%
7	750	680	0.91	24	3	3	85%
8	750	694	0.93	15	11	4	57%
9	750	708	0.94	5	24	1	18%
10	750	722	0.96	1	26	3	8%
11	750	736	0.98	3	26	1	12%
12	750	750	1.00	0	28	2	3%
13	750	764	1.02	1	28	1	5%
14	750	778	1.04	3	25	2	13%
15	750	792	1.06	14	14	2	50%
16	750	806	1.07	22	7	1	75%
17	750	820	1.09	24	5	1	82%
18	750	834	1.11	29	1	0	97%
19	750	848	1.13	28	1	1	95%
20	750	862	1.15	29	1	0	97%
21	750	876	1.17	29	0	0	100%
22	750	890	1.19	30	0	0	100%
23	750	904	1.21	29	0	1	98%

with each data point. The curves cross the line that indicates the point of 50% perception. We define the values of desk-illuminance at those crossings as thresholds for perception of lighting fluctuation. When the desk-illuminance was 400 lx, the threshold was 373 lx ($\sigma = 0.0134$, $E2/E1=0.93$) with decreasing light, 423 lx ($\sigma = 0.0149$, $E2/E1=1.06$) with increasing light. Similarly, when the desk-illuminance was 750 lx, the threshold was 693 lx ($\sigma=0.0195$, $E2/E1=0.92$) with decreasing light, and 798 lx ($\sigma=0.0148$, $E2/E1=1.06$) with increasing light. Thus, we cannot perceive sharp fluctuation when the rate of fluctuation is between 0.92 and 1.06, and we define these two values (0.92 and 1.06) as the minimum ratios for perceived fluctuation.

2.5 Discussion

There was no difference in the minimum ratios for perception of fluctuation between the 400 lx and 750 lx conditions, suggesting that an adaptation level would not influence the perception of fluctuation in a general office environment. Further, we found the tendency that "getting darker" was more difficult to perceive than "getting lighter" under the same rate of fluctuation, although the difference was not large.

For the adaptation levels we studied, we can discriminate the two adjacent areas when the luminance difference reaches 1~2 %. Compared to the simultaneous comparison in such a static conditions, the conditions of the present experiment may be regarded as a sequential comparison with a full visual field. The sensitivity for fluctuation with the sequential comparison was lower than that with the simultaneous comparison.

3. Experiment 2: perception of gradual fluctuation in illumination light.

In Experiment 1, we examined perception of lighting fluctuation for the stimulus changing from the state $E1$ to $E2$ instantaneously. In Experiment 2, we examined perception of the fluctuation for a stimulus changing gradually.

Fig.6 Pattern diagram of fluctuation in illuminance used for Exp.2

3.1 Stimulus for evaluation

To produce a stimulus changing gradually from a state $E1$ to $E2$, we used a stimulus pattern that connects the two states by a trigonometric function used to express a cyclic fluctuation (see Fig. 6). The fluctuation ratio of $E2$ to $E1$ ($E2/E1$) ranged from 0.8 to 1.25 with 12 steps, and the duration of fluctuation from $E1$ to $E2$ was either 2, 8, or 16 seconds. The total number of stimulus samples was 37, including the one in which no fluctuation occurred from $E1$ to $E2$. We fixed the initial illuminance ($E1$) at 750lx, because we found little effect of the adaptation level on perception of lighting fluctuation.

3.2 Methods

The apparatus and the procedures were the same as in Experiment 1. Subjects were 5 males and 5 females with ages into their 40's. The number in the data set was 30, and some subjects repeated the measurement.

3.3 Results

We show the percentage of perceived lighting fluctuation as a function of desk-illuminance after fluctuation for increasing and decreasing light with the fluctuation duration of 2, 8, and 16 sec (total 6 series) in Fig. 7. The normal c.d.f for each condition is also shown. We estimated the threshold and the minimum ratio for perceived fluctuation by the same method of Experiment 1 (Table 2).

The curves differed each other in variance that corresponds to the width of the curves in Fig.7, but similar values were obtained for minimum ratio for perceived fluctuation that was derived by 50 % of the perceived rate. The results indicate that the amount of change was dominant in determining the perception of lighting fluctuation, and that the fluctuation duration, up to 16 sec, had little influence on the minimum ratio for perceiving fluctuation.

Fig.7 Desk-illuminance after fluctuation vs. its rate of the perception on Exp.2

Table 2 Threshold of the lighting fluctuation ratio. (Initial illuminance 750 lx)

Fluctuation duration	Experiment1	Experiment2				Experiment1	Experiment2			
	decreasing light					increasing light				
	0[sec]	2[sec]	8[sec]	16[sec]	0[sec]	2[sec]	8[sec]	16 [sec]		
Threshold of perceived fluctuation(lx)	693	697	690	693	798	813	812	810		
Thershold perceived	0.92	0.93	0.92	0.92	1.06	1.08	1.08	1.08		

3.4 Discussion

Before and after the stimulus presentation, the same illuminance as E1 or E2 was presented for at least 5 to 10 sec. The experimenter instructed the subjects with the word "start" before the stimulus presentation, and with the word "end" after the stimulus presentation. The experimenter asked them to report whether there was lighting fluctuation during a given period. We did not instruct the subjects to fixate on a specific spot in space or to conduct a specific task during the stimulus presentation. However, the subjects reported after the experiment that during the stimulus presentation they fixated their eyes on a part of the wall or tried not to blink in order not to miss the fluctuation. Therefore, not giving a specific instruction was equivalent to instructing the subjects to be sensitive to lighting fluctuation.

Fig. 8 shows the normal c.d.f.s fit to the data of Experiment 2 along with those of Experiment 1. When lighting changed gradually, the thresholds of the 50 % perceived rate were almost the same between the conditions, and the variance between the normal c.d.f.s was apparently larger than that between the curves for Experiment 1.

Fig.8 Comparison of normal cumulative distribution curves.

Although it was not included in our analysis, the rate of error responses was larger in Experiment 2 than in the Experiment 1. In this experiment, when reporting "changed", the subjects were asked to report whether it got darker or lighter. Subjects error response was defined as reporting "became darker" for a stimulus fluctuating to lighter, and as reporting "became brighter" for a stimulus fluctuating to darker.

While it was relatively clear to perceive and report the sharp fluctuation in Experiment 1, it was difficult to perceive the gradual fluctuation in Experiment 2. However, as stated above, the subjects became sensitive to lighting fluctuation and tried to memorize the initial lighting level in the room as the base. Therefore, we suspect that the subjects reported "changed" when they noticed the difference in lighting between the start and the end of one stimulus sample.

Regardless of the interpretations of the data, the results obtained in the present conditions are useful to understand our perceptual abilities for sequential fluctuation of light. In a real office environment, the tasks in Experiments 1 and 2 are rather rare and it may be difficult to apply the data into practical situations.

4. Experiment 3: when a workload was given.

In Experiments 1 and 2, we assumed that the subjects were not given any work loads during the stimulus presentation. To apply our findings into a real working environment, it is important to collect data in a condition that is closer to a real environment. In Experiment 3, we measured the sensitivity to lighting fluctuation while the subjects were given a work load that simulated a real office work.

4.1 Experimental environment

Works in a real office space can be mostly classified into (1) concentrating on a work, (2) communicating with co-workers, and (3) VDT task. In order to simulate these tasks, we introduced three tasks: (1) a test to eliminate specific letters in written sentences ("AMEFURI TEST") that simulates work on a desk, (2) an interview by the experimenter basing on the questions prepared, and (3) answering questionnaires displayed on the VDT.

4.2 Stimulus for evaluation

We prepared three fluctuation patterns, the duration of 0, 2 and 8 sec. All conditions were conducted in one experiment. The initial illuminance was fixed at 750 lx as Experiment 2, and fluctuation ratio ranged from 0.75 to 1.34 with 10 steps, based on the results of a pilot experiment. Thus, 30 stimulus samples in total were used for each task condition.

4.3 Methods

For the tasks of AMEFURI eliminating test and the interview, the age of subjects ranged from 20's to 40's with 8 males and 6 females. The number in the data set was 22, and some subjects repeated the measurement. For VDT task, subjects were 5 males and 4 females, and we collected 18 sample data with 2 repetitions for all subjects.

For the tasks of AMEFURI eliminating test and the interview, after a trial the desk-illuminance automatically returned to the initial illuminance of 750 lx with a slow speed, and stayed at the level for about 10 sec, followed by a stimulus for the next trial. The subjects were instructed to respond by pressing a key when they noticed a lighting change while conducting a task. A PC was connected to the key, and was synchronized with the other PC that controlled the stimulus illumination as well as recorded the desk-illuminance. By this setting, we could record a stimulus pattern when the key was pressed. If the key had been pressed while lighting was returning to the initial level, the response would not have been counted. We did not observe such a response error.

VDT task was conducted with a 22 inch CRT that was treated with an anti-reflect coating and was in a positive mode (white background with the center luminance of 100 cd/m²). Questionnaires were displayed on the screen, and the subjects answered them. If the subjects noticed a lighting change, they were to click the button on the screen by the mouse.

4.4 Results

We show the percentage of perceived lighting fluctuation as a function of desk-illuminance after fluctuation for each task in Fig. 9. Fig. 9 also shows the best-fit curves of the normal c.d.f for each condition. The thresholds and the minimum ratio for perceived fluctuation that were estimated from the curves are shown in Table 3. In general, our results indicate that the sensitivity to fluctuation diminished as the duration of fluctuation increased, although there were some differences between the task conditions.

With AMEFURI eliminating test, the subjects fixated their eyes on the test paper. This situation was similar to those of Experiments 1 and 2 in which the subjects fixated on the wall. The threshold of lighting fluctuation for the duration of 0 sec (sharp change of lighting) was about the same as that obtained in Experiment 1. For the gradual fluctuation conditions, we found that fluctuation was less noticeable with focusing on the visual task than without the task.

Fig.9 Desk-illuminance after fluctuation vs. its rate of the perception in cases of being assigned visual tasks.

With the interview task, the subjects did not fixate on a specific spot, and the probability to miss a brief lighting change may increase, leading to the higher threshold of lighting fluctuation than without the task.

With VDT task, we used a relatively large CRT display, and the screen area in the visual field was large. In addition, luminance fluctuation on the screen was smaller than illuminance fluctuation, because the CRT is a self-illuminating device. These factors may be the causes of the higher threshold of lighting fluctuation with VDT task than without the task.

4.5 Discussion

We chose the results with the interview task as our representative values for perceived lighting fluctuation in an office work situation. This choice was based on three grounds: (1) the three tasks in Experiment 3 would be combined in a real office work, (2) the eyes would not be fixated on a specific spot during the interview task, and (3) the results of the interview task would produce intermediate results among the three task conditions. We regard the

Table 3 Threshold of the lighting fluctuation ratio at a assigned visual tasks.(Base illuminance 750 lx)

Fluctuation duration	decreasing light				increasing light			
	0[sec]	2[sec]	8[sec]	16[sec]	0[sec]	2[sec]	8[sec]	16[sec]
No-task	693 0.92	697 0.93	690 0.92	693 0.92	798 1.06	813 1.08	812 1.08	810 1.08
(a)AMEFURI eliminating test	*709 0.95	653 0.87	594 0.79	— —	816 1.09	866 1.15	916 1.22	— —
(b)Interview	657 0.88	629 0.84	600 0.80	— —	851 1.13	922 1.23	978 1.30	— —
©DVT task	662 0.88	603 0.80	594 0.79	— —	857 1.14	947 1.26	**1066 1.42	— —

Upper row: threshold of perceiving fluctuation (lx)

Lower row: threshold of the lighting fluctuation ratio

*)We had only two useful data. The reliability of the threshold estimates is low.

**) We did not have data above 50% probability. The reliability of the threshold estimates is low.

Note: The data for no-task conditions are copied from the results in Experiments 1 and 2.

Fig.10 Characteristics of perception of lighting fluctuation in offices.

Fig.11 Flicker frequency curve.

results without task, which were obtained in Experiments 1 and 2, as threshold of fluctuation perception in the visual function. The minimum ratios for perceived fluctuation are plotted in Fig. 10 for the interview task and for no-task conditions as a function of the fluctuation duration. In this figure the area defined by the plots for no-task conditions are designated as a “non-perceived” areas, the areas between the plots for no-task conditions and the plots for the interview tasks are designated as “barely perceived” areas, and the areas outside the plots for the interview tasks are designated as “perceived fluctuation” areas.

Fig. 11 shows the flicker sensitivity function standardized to evaluate the flicker produced by voltage flicker in 1964. At the most sensitive frequency, 10 Hz, of the sinusoidal fluctuation, the voltage flicker that 50 % of people can tolerate was determined as 0.45 V (with the commercial frequency voltage of effective value of 100 V). In the flicker sensitivity function, the relative flicker sensitivity for each frequency is shown by setting for 10 Hz as one. From Fig. 11, we estimate the tolerance values of the voltage flicker for the frequencies of 0.25 Hz and 0.0625 Hz at about 4 V and 7.5 V, respectively, which correspond to the fluctuation amplitude of about 12 % and 22 % in the luminous flux ratio with an incandescent lamp used in our experiments. Those frequencies correspond to the fluctuation durations of 2 and 8 sec with AMEFURI eliminating test in Experiment 3, for which we found the minimum ratios for perceived fluctuation were about 13 % and 23 %, respectively. Our results are consistent with the flicker sensitivity function.

5. Summary

To study perception of artificial lighting fluctuation in an office environment, we determined the minimum ratio for perceiving fluctuation by the subjective evaluation experiments, using the method of constant stimuli. We examined the one-directional fluctuation from a state E1 to a state E2, not a periodic fluctuation as flicker.

Human vision cannot perceive the fluctuation of artificial lighting if the fluctuation ratio falls between 0.92 and 1.06, i.e., about 7 %, irrespective of the fluctuation duration. However, in real office environments, the minimum ratios for perceiving fluctuation are between 0.88 and 1.13 (with a sharp fluctuation), and when a gradual fluctuation was used, the minimum ratios increase to 0.8 and 1.3.

It is important to control lighting in order to practice the energy-saving in an office-lighting environment. In adjusting the artificial lighting, we need to control it without producing discomfort for those who work there. Our findings would be useful to make controlling fluctuation of lighting unnoticeable to those people.

What remains to be investigated for practical use is how office workers perceive lighting change when the change occurs more slowly with long duration of fluctuation. We also need to investigate a method of controlling lighting that is suitable to energy-saving.

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