A new method for evaluating productivity and fatigue with human voice under 800 lx and 3 lx lighting conditions

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ABSTRACT
In this study, office work productivity was evaluated by performance and fatigue. Human voice was selected as the indicator of fatigue. Lyapunov exponents can be derived from human voice, and their increase indicates mental and physical fatigue. We also evaluated the mental fatigue by vote of symptoms. Experiments were conducted under two illuminance levels of 800 and 3 lx. Sixteen male subjects were exposed in the experimental chamber conditioned at comfortable temperature and humidity. Addition tasks were given to the subjects to evaluate their performance. Fatigue was measured before and after tasks. Significant differences on task performance between 3 and 800 lx could not be found. However, the subjects complained of the mental fatigue more under 3 lx than that of 800 lx. Also, the Lyapunov exponents increased after tasks than before tasks. Lyapunov exponents have the possibility to evaluate fatigue, and fatigue is useful to measure productivity.

INDEX TERMS
Human voice; Lyapunov exponents; Illuminance; Productivity; Fatigue

INTRODUCTION
In recent times, comfort, healthiness and productivity are of prime importance in office spaces. However, general methods of evaluating productivity have not yet been established. Our previous study showed that evaluation of fatigue feeling was useful to measure productivity in a thermal environment (Nishihara *et al.*, 2002). In this study, both physical and mental fatigue was evaluated to measure productivity because increase of fatigue is expected to lead to lower productivity. It was suggested that measuring fatigue by human voice has the possibility to evaluate productivity in buildings (McCartney and Humphreys, 2002). The new method of evaluating fatigue by human voice was used in the subjective experiments.

METHOD
To evaluate the effect of light environment on productivity, subjective experiments were conducted in a studio at Waseda University during October and November 2002. The purpose of this experiment was to examine the effectiveness of human voice for evaluating fatigue and the evaluation of productivity by fatigue. Sixteen college-age males whose corrected eyesight was more than 0.7 participated in the experiment. All subjects were volunteers who were paid at a fixed rate for their participation. A bonus was paid for high-achieving subjects to keep their motivation high on the same level. Every subject participated in three conditions on the same time of a week. Experimental conditions are shown in Table 1. Practice condition was the first one under 800 lx to exclude learning effect of tasks. Condition of 800 lx was within the proper illuminance for an office of Japanese Industrial Standards (JISC, 1958). The condition of 3 lx was likely to be unsuitable for office work. Both conditions were conducted in a random order after practice. The desktop illuminance was measured by a digital illuminometer T-1M (MINOLTA). Air temperature was kept at 23.6 ± 0.1°C, radiation

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temperature was 23.7 ± 0.1°C, relative humidity was 37 ± 0.2% RH during the experimental period.

Figure 1 shows the experimental procedure. After explanation and flicker test in the anteroom, subjects entered the studio and they were exposed for 105 min. The first 20 min was given for subjects to adapt to the light environment before the tasks. Each measurement for evaluation of productivity was conducted between each task. The task was addition of three-digit numbers, and different types were prepared for each condition. Subjects did the task for as many times as possible for 20 min. Also, the subjects read aloud one Japanese essay that is supposed to be read within 10 min (Terada, 1964).

Table 1 Experimental conditions

Conditions	Desktop Illuminance [lx]
Practice	788 (12.8)
800 lx	791 (20.1)
3 lx	3.2 (0.1)

( )standard deviation

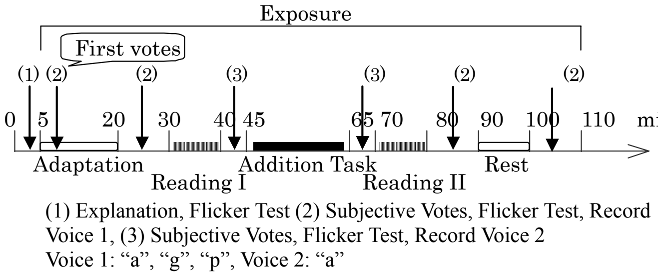


Figure 1 Experimental procedure.

Several methods were used to evaluate productivity. Subjective votes illustrated in Figure 2 were used to evaluate the light environment. Votes on eyestrain were also asked. These votes are shown in Table 2. Subjects answered 10 questions on eyestrain, and the rate of complaints on eyestrain was analysed. To evaluate the magnitude of fatigue, mental fatigue and physical fatigue were evaluated. Subjects filled in the sheets of 'Evaluation of Subjective Symptoms of Fatigue' suggested by the working group for occupational fatigue of the Japan Society for Occupational Health (Yoshitake, 1993). For evaluation of mental fatigue, this evaluation method is used in the field of labour and ergonomics in Japan. It consists of three categories, whose subjective symptoms of fatigue are shown in Table 3. Based on Yoshitake's method, the rate of complaints was calculated by Eqn (1). According to the rate of complaints among three categories, three types of fatigue are suggested (Yoshitake, 1993)—general pattern of fatigue: 'I > III > II'; typical pattern of fatigue for mental work and overnight duty: 'I > II > III'; and typical pattern of physical work: 'III > I > II'. 'General rate of complaints' was defined as the rate of complaints on all 30 symptoms.

Human voice and Flicker exponents were used for the evaluation of physical fatigue. Physical signals, e.g. human voice and pulse, generally have chaotic fluctuations. These waves of time series are expressed as chaotic attractors by Takens plot (Takens, 1981). Moreover, the magnitude of fluctuations on chaotic attractors can be quantified as Lyapunov exponents. Increase of Lyapunov exponents had possibilities to indicate increase of fatigue (Shiomi, 1999; Shiomi and Hirose, 2000). However, interpretation of Lyapunov exponents has not been clearly explained yet. The prediction tool for fatigue and drowsiness is based on the calculation system of Liapunov exponents from the subject's voice (Shiomi, 1999). In this system, vocal signals were sampled at a rate of 11 025 Hz (8 bits/sample), and about 1 s of sampled data were necessary to calculate the Liapunov exponents when the strange attractor was formed in four-dimensional Takens space (Takens, 1981). The voices recorded in the experiment were 'a' (a, i, u, e, o), 'g' (ga, gi, gu, ge, go) and 'p' (pa, pi, pu, pe, po) in Japanese. These were selected by the difference of pronunciation structures (Hongou *et al.*, 1996). The Flicker exponents were also used as another parameter of physical fatigue. It was reported that Flicker exponents seem to be decreased due to fatigue (Ookubo, 1999).

Differences of mean values among the experimental conditions were analysed using one-way ANOVA. When a statistically significant result was found, post hoc comparisons were made by using Fisher's protected LSD. The level of significance was set at $p < 0.05$. The correct answer rate per minute at each task was calculated for the analysis of task performance.

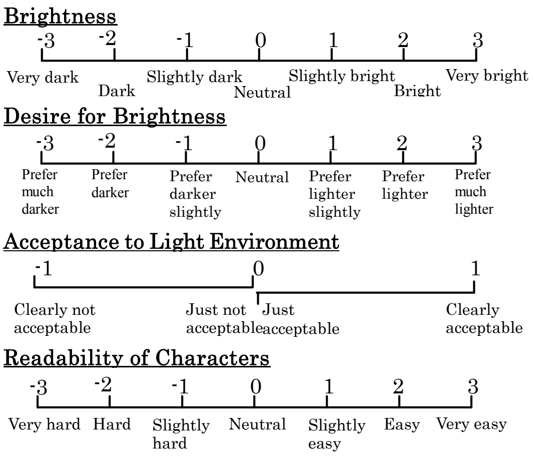


Figure 2 Subjective votes on light environment.

Table 2 Subjective votes on eyestrain

Does your eye hurt?
Does your eye become bleary?
Does it flicker?
Do your eyes feel dry?
Are there many blinks?
Can you focus on things with a long distance?
Can you focus on things with a short distance?
Can you see things clearly?
Is it hard to gaze at things?
Do things look dazzling?

Table 3 Three categories of subjective symptoms of fatigue

Category I	Category II	Category III
Feel heavy in the head	Feel difficulty in thinking	Have a headache
Whole body feels tired	Become weary of talking	Feel stiff in the shoulders
Legs feel tired	Become nervous	Feel a pain in the back
Yawning	Unable to concentrate attention	Feel oppressed in breathing
Feel the brain hot or muddled	Unable to have interest in things	Feel thirsty
Become drowsy	Get forgetful	Have a husky voice
Feel strained in the eyes	Lack of self-confidence	Feel dizzy
Become rigid or clumsy in motion	Anxious about things	Have a spasm on the eyelids
Feel unsteady in standing	Unable to straighten up in a posture	Have a tremor in the limbs
Want to lie down	Lack patience	Feel ill

$$\text{Rate of complaints} = \frac{\text{Total number of a corresponding fatigue symptom of total subjects}}{\text{Total number of symptoms on the evaluation sheet} \times \text{Total number of subjects}} \times 100\ (\%) \qquad (1)$$

RESULTS AND DISCUSSIONS

Subjective Votes on Light Environment

Results of subjective votes on light environments are shown in Table 4. The value of ‘Brightness’ was significantly higher under practice and 800 lx than that at 3 lx ($p < 0.01$). The value of ‘Desire for brightness’ was significantly higher under 3 lx than practice and 800 lx ($p < 0.01$). The value of ‘Acceptance to light environment’ was significantly higher under practice and 800 lx than 3 lx ($p < 0.01$). The value of ‘Readability of characters’ was significantly higher under 800 lx than under 3 lx ($p<0.01$). Subjects complained of 3 lx condition about the light environment, and they did not accept 3 lx.

Task Performances

Difference in the performance of addition task was not significant among different light environments. The performance of addition tasks is shown in Figure 3.

Evaluation of Subjective Symptoms of Fatigue

General rates of complaints before and after the tasks are shown in Figure 4. General rate of complaints of 3 lx conditions was higher than 800 lx conditions. Also, the rate of complaints increased after tasks under any conditions. The order among three categories of the subjective symptoms of fatigue is shown in Table 5. Under 800 lx conditions, before and after tasks, the order among three categories was I > III > II, that is, grouped as 'General pattern of fatigue'. Under 3 lx conditions, it was I > III > II before tasks. However, it was I > II > III after tasks, that is, grouped as 'Typical pattern of fatigue for mental work and overnight duty'. The subjects complained of the feeling of mental fatigue highest after all tasks under 3 lx conditions. These results imply that the subjects felt mental fatigue strongly against the tasks under 3 lx light environment. In addition, the rate of II against the rate of T, the total rate of complaints (II/T) after all tasks under 3 lx was the highest among other conditions. It was reported that II/T increases if general rate of complaints are high (Yoshitake, 1993).

Evaluation of Subjective Symptoms of Eyestrain

The general rate of complaints on eyestrain is shown in Figure 5. Under 3 lx conditions, general rates of complaints on eyestrain after 'Reading I', 'Addition Task', 'Reading II', 'Rest' were significantly higher than the first vote ($p < 0.01$). They were also significantly higher than 'After Adaptation' ($p < 0.01$, $p < 0.01$, $p < 0.01$, $p < 0.05$). These results imply that subjects felt complaints of eyestrain after the tasks under 3 lx conditions.

Table 4 Results of subjective votes on light environment

	Practice	800 lx	3 lx
Brightness	0.51 (0.86)	0.70 (0.91)	-1.88 (0.65)
Desire for Brightness	0.14 (0.60)	0.07 (0.68)	1.76 (0.73)
Acceptance to Light Environment	0.41 (0.37)	0.47 (0.34)	-0.38 (0.39)
Readability of Characters	0.98 (1.01)	0.69 (0.91)	-1.47 (0.88)

( )standard deviation

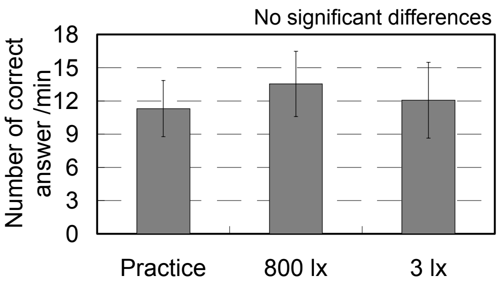


Figure 3 Performance of addition task.

Table 5 General rate of complaints and the order among three categories of subjective symptoms of fatigue

		The Rate of Complaints [%]				
		I	II	III	T	The Order
Practice	First Votes	7.1	6.4	7.9	7.1	III > I > II
	After Adaptation	13.6	7.9	5.0	8.8	I > II > III
	After Reading I	20.0	15.0	10.7	15.2	I > II > III
	After Addition Task	23.6	11.4	10.7	15.2	I > II > III
	After Reading II	26.4	17.1	15.7	19.8	I > II > III
	After Rest	27.1	15.0	6.4	16.2	I > II > III
800 lx	First Votes	5.7	1.4	4.3	3.8	I > III > II
	After Adaptation	13.6	2.1	4.3	6.7	I > III > II
	After Reading I	19.3	6.4	8.6	11.4	I > III > II
	After Addition Task	20.0	5.7	7.9	11.2	I > III > II
	After Reading II	22.1	10.7	13.6	15.5	I > III > II
	After Rest	20.0	5.0	5.7	10.2	I > III > II
3 lx	First Votes	12.1	3.6	4.3	6.7	I > III > II
	After Adaptation	19.3	1.4	4.3	8.3	I > III > II
	After Reading I	27.9	12.1	12.9	17.6	I > III > II
	After Addition Task	35.0	11.4	10.0	18.8	I > II > III
	After Reading II	38.6	19.3	14.3	24.0	I > II > III
	After Rest	30.0	12.9	8.6	17.1	I > II > III

[I: the rate of complaints on Category I, II: the rate of complaints on Category II, III: the rate of complaints on Category III, T: the total rate of complaints]

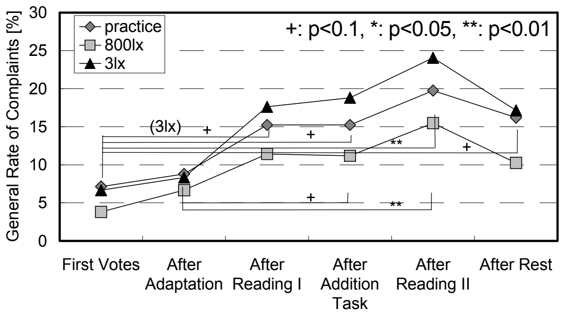


Figure 4 General rate of complaints.

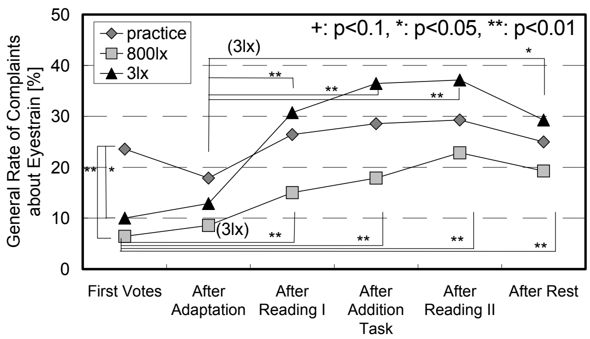
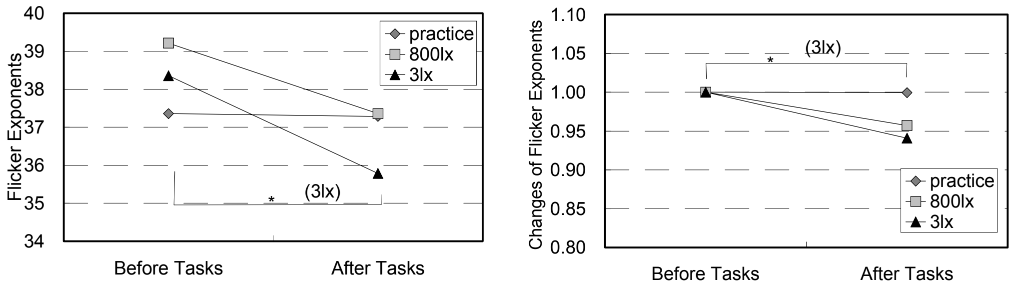


Figure 5 General rate of complaints on eyestrain.

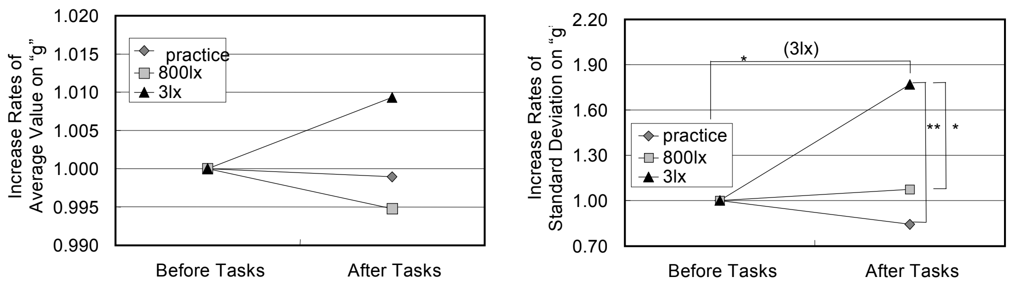
Evaluation of Physical Fatigue by Flicker Exponents

To evaluate fatigue after the entire set of tasks, the Flicker exponents before and after all tasks, i.e. after ‘Adaptation’ and ‘Reading II’, were analysed. Also, the increase rates were examined as well as Lyapunov exponents. The Flicker exponents after all tasks were significantly lower than that before all tasks at 3 lx ($p < 0.05$). The increase rate of the Flicker exponents after all tasks was significantly lower than that before all tasks at 3 lx ($p < 0.05$). The Flicker exponents and increase rates of Flicker exponents are shown in Figure 6. These exponents under 3 lx were co-varied with subjective votes on symptoms of fatigue under 3 lx. This may mean that decrease of Flicker exponents indicates increase of fatigue.

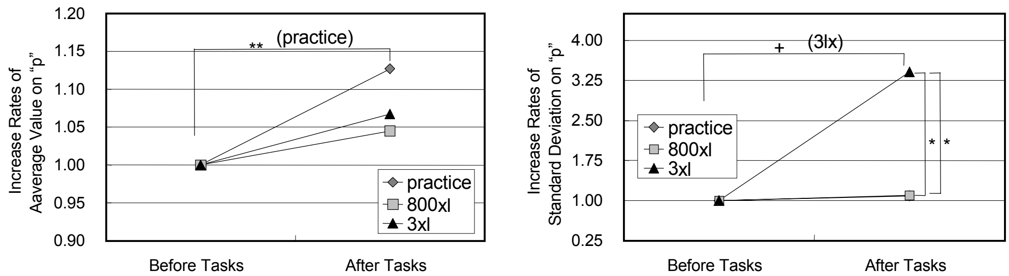


Flicker exponents Increase rates of Flicker exponents

Figure 6 The Flicker exponents and the increase rates of the Flicker exponents before and after all tasks (+: $p < 0.1$, *: $p < 0.05$, **: $p < 0.01$).



Increase rates of average value on ‘g’ Increase rates of standard deviation on ‘g’



Increase rates of average value on ‘p’ Increase rates of standard deviation on ‘p’

Figure 7 Changes in both the average value and the standard deviation of Lyapunov exponents on ‘g’ and ‘p’ (+: $p < 0.1$, *: $p < 0.05$, **: $p < 0.01$).

Evaluation of Physical Fatigue by Human Voices

To evaluate fatigue after the entire set of tasks, average value and standard deviation within subjects of Lyapunov exponents before and after all tasks, i.e. after ‘Adaptation’ and ‘Reading II’, were analysed. Also, the value before all tasks was regarded as a standard value and the increase rates were examined to exclude the difference of value between subjects. The increase rates of the standard deviation on ‘g’ and ‘p’ at 3 lx were significantly higher than those at 800 lx ($p < 0.05$). The increase rates of the standard deviation on ‘g’ and ‘p’ after tasks were also significantly higher than those before tasks ($p < 0.05$). The changes in both the average value and the standard deviation of the Lyapunov exponents on ‘g’ and ‘p’ are shown in Figure 7. These increase rates of the standard deviation of the Lyapunov exponents under 3 lx have good relationship with subjective votes on symptoms of fatigue under 3 lx. As a result, this may mean that the increase of change in standard deviation of Lyapunov exponents on 'g' and 'p' indicates the increase of fatigue.

Although the objective indicators of fatigue had strong relationship with subjective estimates of fatigue, they did not with performance. The reasons were concluded to be the following: (1) the 105-min exposure was short; (2) the subjects were highly motivated; (3) low levels of lighting present few problems for young eyes; (4) 16 subjects may not be enough for an experimental effect on performance. However, the fatigue stored in daily works has the sufficient possibility to lower performance or healthiness. To establish a new method of evaluating productivity by fatigue for assessing the indoor environment, it needs to be cleared that fatigue will predict the actual productivity. Also, the results showed the high indicator of fatigue under low illuminance conditions. This may mean that assessing the indoor environment by fatigue is available.

CONCLUSIONS

A subjective experiment was conducted under 800 lx and 3 lx to evaluate subjects' productivity. The results were the following: (1) there was no significant difference in the task performance among three conditions; (2) general rates of complaints and those on eyestrain under 3 lx condition were higher than those under the other two conditions; (3) the increase rates of standard deviation of Lyapunov exponents on 'g' and 'p' at 3 lx were significantly higher than those at 800 lx, and Flicker exponents at 3 lx decreased after all tasks. The works under 3 lx condition caused higher magnitude of fatigue than under the 800 lx condition.

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