Productivity and fatigue

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2 authors:

Shin-ichi Tanabe
Waseda University

Naoe Nishihara
University of the Sacred Heart

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INDOOR AIR

Productivity and fatigue

Abstract In studying productivity, effects of environmental factors have focused only on performance. However, previous studies of the impact of the environment upon performance of mental tasks generally conclude that productivity research is somewhat confusing because the results are sometimes conflicting. In experiments, subjects may be highly motivated for a short time period, so it is very difficult to find differences in performance. In this paper, our research group used new methods to evaluate the factors affecting productivity. Not only task performance but also parameters of fatigue were investigated. Three subjective experiments using these evaluation methods to investigate the effect of productivity are summarized.

S. Tanabe and N. Nishihara
Department of Architecture, Waseda University, Tokyo, Japan

Key words: Productivity; Task performance; Fatigue; Cerebral blood flow.

Professor Shin-ichi Tanabe
Department of Architecture,
Waseda University, Tokyo, Japan
e-mail: tanabe@waseda.jp

Practical implications
This paper introduces interesting new methods for evaluation of people's fatigue.

Introduction

Productivity is defined as the extent to which activities have provided performance in terms of system goals (Parsons, 1993). Effects of environmental factors, namely indoor climate, accidents, human efficiency and comfort were reviewed by Wyon (1986) and his work has been referenced widely. Wargocki et al. (2000) reported that the performance of four simulated office tasks improved with increasing ventilation rates, and the effect reached formal significance in the case of text typing. On the other hand, some others reported no significant effects of productivity for short-term tests. People are highly motivated during a short-term experiment, so it may be very difficult to measure the difference in actual performance. However, we already know that productivity is reduced under poor environmental conditions in daily life. After long office hours, we become tired and decrease our performance. We developed a method of evaluating fatigue in experiments. In this paper, we introduce methods to evaluate the factors affecting productivity. Not only task performance but also the parameters of fatigue are discussed. Three subjective experiments using these evaluation methods are summarized to investigate the effect of productivity.

Evaluation of factors affecting productivity

Task performance

To evaluate task performance, several tasks simulating office work were assigned to the subjects: addition, text typing, a cursor positioning test, and the Walter Reed Performance Assessment Battery test (Thorne et al., 1985). These performance tests are described in Table 1.

Subjective symptoms of fatigue

To evaluate the feeling of fatigue, 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. This evaluation method is used in the fields of science and of labor and ergonomics in Japan. It consists of three categories; I-group consists of 10 terms on "drowsiness and dullness", II-group consists of 10 terms on "difficulty in concentration", and III-group consists of 10 terms on "projection of physical disintegration". Three categories of subjective symptoms of fatigue are shown in Table 2. Based on Yoshitake's method, the rate of complaints was calculated by equation 1. By the order of the rate of complaints among the three categories, three types of fatigue were suggested (Yoshitake, 1973): 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 about all 30 symptoms – see equation 1.

Evaluation of physical fatigue by voice analysis

The human voice and Flicker exponents were used for the evaluation of physical fatigue. Physical signals, e.g.,

Table 1 Task performance tests for subjects

Addition test		1) Single digit addition test 2) Triple digit addition test
Positioning test		The target (black circle) was displayed randomly on PC-display, and subjects clicked on it as quickly as possible.
Text typing test		Subjects retyped model text presented in an upper window into a lower window. For subjects who were unused to keyboards and English, we used only number and slash for the model text.
	Two-letter search	Two target letters were presented at the top of the screen, along with a string of 20 letters in the middle screen. Subjects determined whether both target letters were present in the string or not.
	Four-choice serial reaction time	Subjects were given four boxes on the screen. Single lights were illuminated randomly and subjects were to press the corresponding key of 10-key (1, 2, 4, 5).
PAB	Interval production	Subjects estimated one-second time by pressing key.
	Manikin	A spatial rotation task. Subjects had to give a bilateral response.
	Code substitution	A paired associate learning task.
	Matching to sample	A forced choice pattern comparison task.
	Running memory	A measure of immediate or working memory with a distracter.

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

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. An increase of Lyapunov exponents can indicate an increase of fatigue (Shiomi, 1999; Shiomi & Hirose, 2000). However, a clear explanation of Lyapunov exponents has not yet been given. 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 one second of sampled data was necessary to calculate 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 because of the difference of pronunciation structures (Hongou et al., 1996).

Table 2 Three categories of subjective symptoms of fatigue

I	II	III
My head is drooping	I can't think clearly	I have a headache
My whole body is getting tired	Talking would take some effort	My shoulder muscles are tense
My legs are getting tired	I am starting to feel nervous	My back hurts
I can't stop yawning	I can't concentrate	Breathing takes an effort
My mind is blank	I am losing interest in my work	I feel thirsty
I am starting to feel drowsy	I am starting to forget things	My voice is probably hoarse
My eyes are getting tired	I am uncertain	I feel giddy
I feel stiff and clumsy	I am worried	The small muscles around my eyes are twitching
I would be unsteady on my feet	I am sitting badly	My limbs are shaking
I feel like lying down	I feel impatient	I feel unwell

Cerebral blood oxygenation changes

The near infrared spectrometer (NIRO-300) is shown in Fig. 1. Near infrared light was produced by laser diodes and carried to the tissue via optical fibers (Elwell, 1995). The light emerging from the tissue was returned to the instrument through another optical fiber by detector and incident and integrated values of transmitted light intensities were recorded every second. The sampling rate was 2000 times per second. Changes in the concentration of the chromophores oxygenated hemoglobin "ΔO_2Hb" and deoxyhemoglobin "ΔHHb" were calculated by Modified Beer-Lambert equation in $\mu M = 10^{-6}$ mol units (Delpy et al., 1988). The changes in concentration of total hemoglobin were calculated: $\Delta \text{total Hb} = \Delta O_2Hb + \Delta HHb$. The probes were placed on both sides of the subject's forehead.

Relationship between the changes in cerebral blood oxygenation and the difficulty level of a task was evaluated in subjective experiments (Nishihara & Tanabe, 2004). Four tasks were given to the subjects: single-digit addition, double-digit multiplication, triple-digit addition, and triple-digit multiplication. It was evaluated that the more difficult the type of task, the more oxygenated hemoglobin and total hemoglobin concentration were required for their performance. There was a significant correlation between the subjective value of mental demand for tasks and the left side Δ total hemoglobin concentration. The change rate of total hemoglobin during each task is shown in

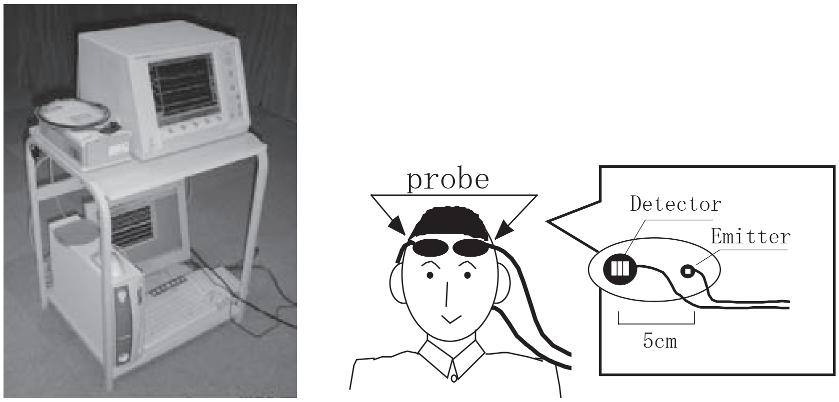

Fig. 1 Near infrared spectrometer NIRO-300.

Fig. 2. It was shown that tasks involving a higher mental demand required a higher cerebral blood flow. The correlation between the values of change rates of mental demand and left side Δtotal Hb, based on the single-digit addition task, are shown in Fig. 3. Monitoring cerebral blood oxygenation changes could be applied to the evaluation of the input-side parameter of productivity, to indicate the degree of mental effort required to perform the task.

Experiment I (Moderately high temperature)

Method

College-age subjects, 20 males and 20 females, participated in the experiments (Nishihara et al., 2002). The chamber was conditioned at operative temperatures of 25.5°C, 28°C, and 33°C with still air. In addition to these three conditions, a practice session at an operative temperature of 25.5°C was conducted. Relative humidity was 50%. Subjects wore a uniform with an insulation value of 0.76 clo. Task performance tests on computer were conducted for 1.5 h.

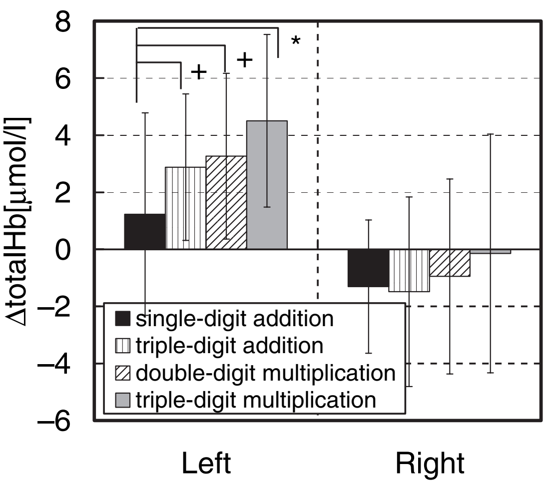

Fig. 2 Δtotal Hb during each task.

The experimental procedure is shown in Fig. 4. After entering the climate chamber, subjects waited in a sedentary position for 30 min, and then reported their first thermal sensation in the chamber and their feeling of fatigue. Four tests were carried out: the addition test for 10 min, the positioning test for 5 min, the text typing test for 5 min, and the Walter Reed Performance Assessment Battery test (PAB) for about 15 min. After each test, an intermission of 5 min was taken and the subjects reported their thermal sensation, their feeling of fatigue, and their evaluation of the task load. Subjects filled in the sheets for evaluation of subjective symptoms of fatigue 30 min after entering the climate chamber as "before task" and after all computer tasks were finished, as "after task".

Results

Environmental sensation The results of the whole-body thermal sensation vote, comfort sensation vote, thermal acceptability and sweating sensation vote are

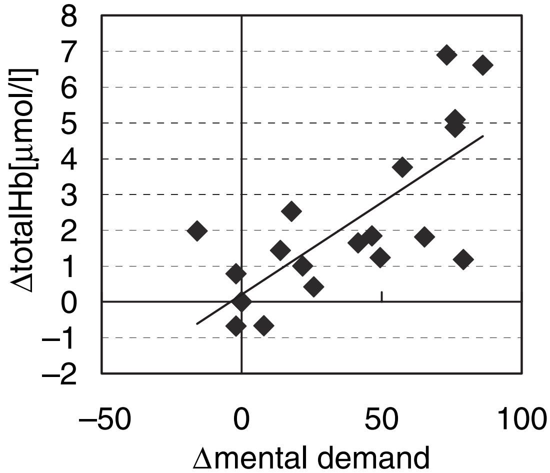

Fig. 3 Correlation between values of change rates of mental demand and left side of Δtotal Hb, based on the single-digit addition task.

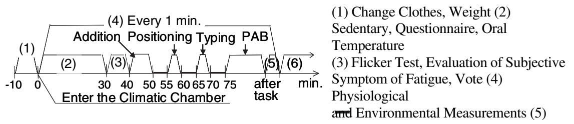

Fig. 4 Experimental procedure.

shown in Table 3. ASHRAE and Gagge scales were applied. At 25.5°C, the average values of the thermal sensation vote and the sweating sensation vote of female subjects were significantly lower than that of male subjects ($p < 0.01$).

Task performances For female subjects, there was no significant difference in the performance of all computer tasks under the environmental conditions. For male subjects, there was no significant difference in the performance of the addition test and the positioning test under the environmental conditions. As regards the performance of PAB, there was no significant difference under all environmental conditions except for "four choice serial reaction time". The performance of this test at 33°C was significantly lower than at 28°C ($p < 0.05$). The performance of the text typing test at 25°C was significantly lower than at 28°C and 33°C ($p < 0.05$). The performance of text typing and "four choice serial reaction time" (PAB) are shown in Figs 5 and 6. In this study, the effects of thermal environment on task performance were contradictory among the task types as in previous findings (Lorsch & Abdou, 1994, and CIBSE, 1999). It is difficult to evaluate the effect of thermal environment on productivity by measuring only task performance.

Evaluation of subjective symptoms of fatigue Especially before the task, the general rate of complaints at 33°C was highest, next highest at 28°C, and lowest at 25°C. The order among the three categories of subjective symptoms of fatigue is shown in Table 4. Before the task, at 25°C and 28°C, the order among the three categories of subjective symptoms of fatigue was I > III > II, grouped as "General pattern of fatigue" in both female and male subjects. On the other hand, at 33°C, it was I > II > III, grouped as "Typical pattern of fatigue for mental work and overnight duty" in both female and male subjects. After the task, in male subjects, the order among the three categories of subjective symptoms of fatigue was I > II > III, grouped as "Typical pattern of fatigue for mental work and overnight duty" under all environmental conditions. In female subjects, it was I > III > II at 25°C and 28°C, and I > II > III at 33°C. The subjects complained of a feeling of mental fatigue, most complaints being at an operative temperature of 33°C.

Table 3 Subjective vote on thermal environment (Mean ± S.D)

	Conditions	Thermal sensation	Comfort sensation	Thermal acceptability	Sweating sensation
Male	25.5°C	0.1 ± 0.83	− 0.4 ± 0.33	0.5 ± 0.33	0.4 ± 0.37
	28.0°C	1.2 ± 0.69	− 0.8 ± 0.59	0.1 ± 0.44	0.8 ± 0.58
	33.0°C	2.5 ± 0.49	− 2.2 ± 0.66	− 0.6 ± 0.38	1.9 ± 0.66
Female	25.5°C	− 0.6 ± 1.03	− 0.5 ± 0.58	0.5 ± 0.44	0.1 ± 0.17
	28.0°C	1.1 ± 0.78	− 0.7 ± 0.55	0.2 ± 0.44	0.6 ± 1.29
	33.0°C	2.5 ± 0.63	− 1.9 ± 0.76	− 0.5 ± 0.41	1.6 ± 0.99

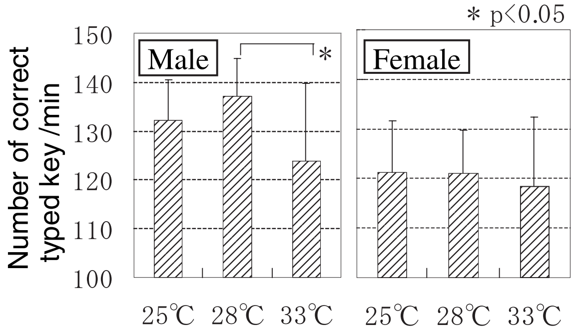

Fig. 5 Performance of four choice (PAB).

Evaluation by near infrared spectroscopy To evaluate the changes in cerebral blood oxygenation during a task by means of near infrared spectroscopy (NIRS), experiments were conducted with the participation of six college-age subjects. The chamber was conditioned at operative temperatures of 25°C and 33°C. In addition, a practice session at an operative temperature of 25°C was carried out. The procedure of the experiment was the same as for Experiment II, except that the measurement of the changes in cerebral blood oxygenation using near infrared spectroscopy was added. The increase rates of ΔO_2 Hb and Δtotal Hb at the left side

Table 4 The order among the three categories of subjective symptoms of fatigue

Male/ Female	Conditions	I-group (%)	II-group (%)	III-group (%)	The order among three categories
Before task	25.5°C	15.5/16.5	3.5/1.5	5.5/5.5	I > III > II/I > III > II
	28.0°C	23.0/26.5	5.0/8.0	7.0/11.0	I > III > II/I > III > II
	33.0°C	24.0/32.0	12.0/14.0	11.5/12.0	I > II > III/I > II > III
After task	25.5°C	21.5/31.5	14.0/12.5	13.5/14.0	I > II > III/I > III > II
	28.0°C	28.0/31.5	15.5/15.0	13.5/18.5	I > II > III/I > III > II
	33.0°C	24.5/34.0	21.5/19.0	14.5/16.5	I > II > III/I > II > III

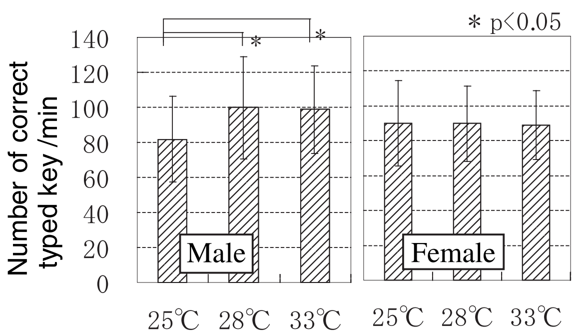

Fig. 6 Performance of text typing.

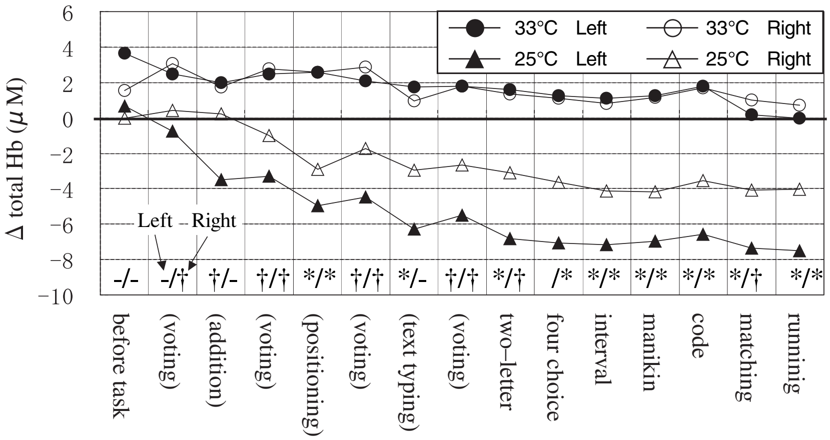

Fig. 7 The changes in the concentration of total hemoglobin during each task. For each left and right side of cerebral hemoglobin concentration, the results of a paired *t*-test between 25°C and 33°C during each task are shown. (– : no significant, †: $p < 0.1$, *: $p < 0.05$, **: $p < 0.01$).

of the head at 33°C were significantly higher than those at 25°C in positioning, text typing, and PAB tests. There was no significant difference in ΔHHb between 33°C and 25°C. Changes in the concentration of total hemoglobin are shown in Fig. 7. A previous study reported that increments of ΔO_2Hb and Δtotal Hb, and decrements of ΔHHb were typically found by NIRS during brain activation and mental work. The results at 33°C indicated typical cerebral blood oxygenation during brain activation and mental work as in the previous study.

Experiment II (Lighting conditions under 800 lux and 3 lux)

Method

Two extremely different conditions of light environment were selected for the experiment. The first one was 800 lux and the second was 3 lux. A practice session was held in 800 lux. The air temperature was 23.6°C and the relative humidity was 37%RH during the 110 min of the experimental period (Nishikawa et al., 2003). 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 them highly motivated at the same level.

Figure 8 shows the experimental procedure. After an introduction, instructions and a flicker test in the anteroom, subjects entered the studio and were exposed for 105 min. The first 20 min allowed subjects to adapt to the light environment before undertaking the tasks. Each measurement for evaluation of productivity was taken between each task. The task involved addition of three-digit numbers on paper, and for each condition the numbers were changed. Subjects did as much as possible of the task in the allotted 20 min. Also, subjects read aloud one Japanese essay that is supposed to be read within 10 min (Terada, 1964).

Results

Environmental sensation Subjective votes illustrated in Fig. 9 were used to evaluate the lighting environment. Results are shown in Table 5. The value of ‘‘brightness’’ was higher at 800 lux than at 3 lux. Subjects described the conditions at 3 lux as darkness. The value of ‘‘Desire for brightness’’ was higher under 3 lux than under 800 lux. Subjects accepted 800 lux conditions for the light environment. On the other hand, they did not accept 3 lux.

Task performances The performance of addition tasks is shown in Fig. 10. Surprisingly, the difference between 800 lux and 3 lux was not significant.

Evaluation of subjective symptoms of fatigue The general rate of complaints at 3 lux was higher than at 800 lux. Moreover, after performing the tasks under either of the conditions, the rate of complaint increased. The order among the three categories of the subjective symptoms of fatigue is shown in Table 6. In the 800 lux condition, before and after performing the tasks, the order among the three categories was I > III > II, grouped as ‘‘General pattern of fatigue’’. In the 3 lux condition, it was I > III > II before tasks and I

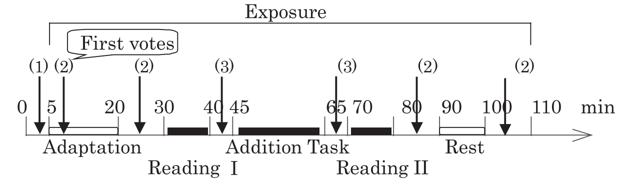

Fig. 8 Experimental procedure.

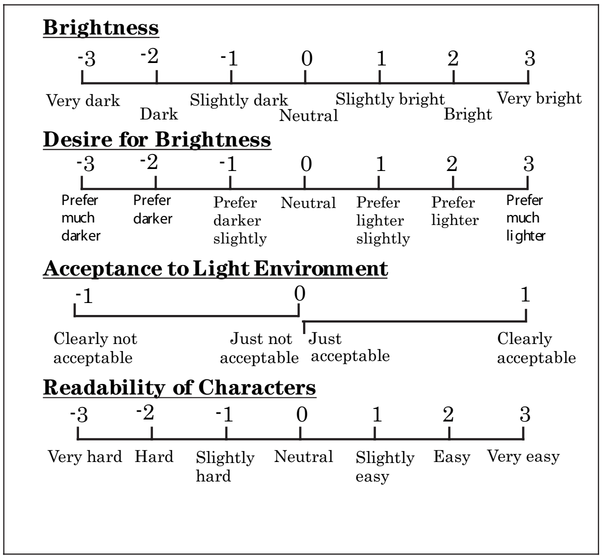

Fig. 9 Subjective votes on light environment.

Table 5 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	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

Table 6 General rate of complaints and the order among the three categories 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
31x	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

> II > III after the tasks; this is classed as "Typical pattern of fatigue for mental work and overnight duty". The subjects complained most of the feeling of mental fatigue after all tasks in the 3 lux conditions. These results imply that the subjects felt mental fatigue most strongly after tasks performed in the 3 lux condition.

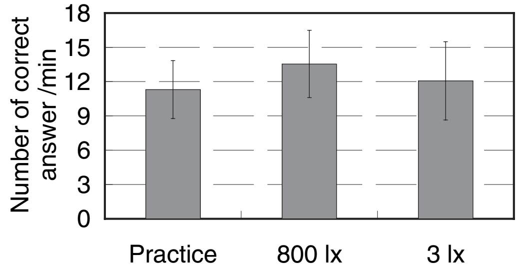

Fig. 10 Performance of addition task.

Evaluation of physical fatigue by human voices The Lyapunov exponents before and after three tasks were analyzed (Shiomi & Hirose, 2000). The increase rates of the standard deviation on "g" and "p" at 3 lux were significantly higher than those at 800 lux ($P < 0.05$). The increase rates of the standard deviation on "g" and "p" after tasks were also significantly higher than those before tasks ($P < 0.05$) as shown in Fig. 11. It was clear from subjective votes on symptoms of fatigue that subjects felt fatigue after performing tasks at 3 lux. As a result, the increase rates of standard deviation within subject of Lyapunov exponents on "g" and "p" can be used to evaluate fatigue.

Evaluation by near infrared spectroscopy To evaluate the changes in cerebral blood oxygenation while performing tasks in the 3 lux and 800 lux conditions by means of near infrared spectroscopy (NIRS), experiments were conducted with six college-age male subjects. The experimental procedure was the same as for Experiment II, except that the measurement of the changes in cerebral blood oxygenation by near infrared spectroscopy were added. The ΔO_2Hb, ΔHHb and Δtotal Hb are shown in Fig. 12. There were significant differences of ΔO_2Hb in the 3 lux condition, between the reading and addition tasks. Although there was no significant difference between the 3 lux and 800 lux conditions, the results of cerebral blood oxygenation changes show that the brain has a tendency to be activated more in the 3 lux condition. Further studies with a greater number of subjects are required.

Conclusions

In this paper, we introduced some new evaluation methods for factors affecting productivity. Not only task performance but also the parameters of fatigue, namely subjective symptoms of fatigue, physical fatigue as indicated by voice analysis and cerebral blood oxygenation changes, were discussed. Two subjective experiments under moderately high temperature and under 3 lux and 800 lux conditions using these evaluation methods were reported.

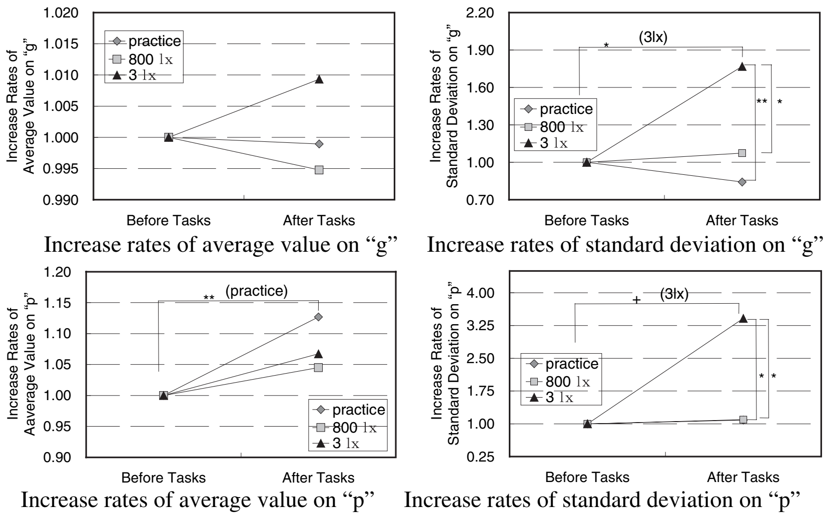

Fig. 11 Changes in both the average value and the standard deviation of Lyapunov exponents on "g" and "p". (+ : $p < 0.1$, *: $p < 0.05$, **: $p < 0.01$).

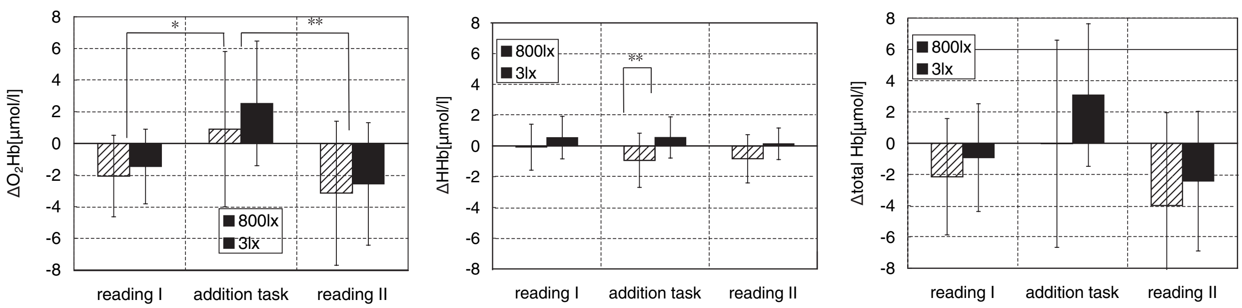

Fig. 12 Cerebral blood oxygenation changes under 3 lux and 800 lux conditions. Left: ΔO2Hb, Middle: ΔHHb, Right: Δtotal Hb. (*: $p < 0.05$, **: $p < 0.01$).

In addition to evaluating performance, the cost of maintaining performance, namely fatigue, is important in evaluating and predicting productivity.

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