Productivity and fatigue

Shin-ichi Tanabe*

Department of Architecture, Waseda University, Tokyo, Japan

ABSTRACT
For a long time in the history of the productivity study, the effects of environmental factors only on the performance had been focused. However, previous studies on 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 the controlled chamber, subjects may be highly motivated for a short time period, so it is very difficult to find the difference of performances. In this paper, we introduce a second parameter—fatigue. Three subjective experiments are reported. To evaluate fatigue is a key to evaluate productivity.

INDEX TERMS
Productivity; Task performance; 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 papers have been widely referred to. 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-time tests. People are highly motivated during short-time experiments, so it may be very difficult to measure the difference of performance itself. However, we already know that productivity can be reduced under poor environment in daily life. After long office hours, we become tired and our performance decreases. In this paper, three different subjective experiments are summarized to investigate the effect of productivity. We developed the method to evaluate fatigue in the study.

EXPERIMENTAL CONDITIONS

Moderate High Temperature

Subjects of college-going age, 20 males and 20 females, participated in the experiments (Nishihara *et al.*, 2002). The study chamber was conditioned at operative temperature of 25.5, 28 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 0.76 clo. Task performance tests were conducted for 1.5 h.

Preferred Air Velocity

The experimental conditions are shown in Table 1 (Nishihara and Tanabe, 2003). The fans were set at the left side of subject. For the CAV conditions, they were not allowed to control air velocity. For the PAV conditions, they were allowed to control it by using a remote controller at the three levels of 'Low', 'Medium' and 'High'. Chamber was conditioned at air temperature of 31°C and relative humidity of 50%. Subjects were also exposed to air temperatures of 28°C. They also participated a practice session. Subjects wore typical office clothing ensembles with 0.71 clo. Experiments were conducted for 135 min with tests.

Lighting under 800 and 3 lx

Two extremely different conditions of light environment were adopted for the experiments. The first was 800 lx and the second was 3 lx. Practice session was done under 800 lx. Air temperature

* E-mail: tanabe@waseda.jp
† Contact author email: tanabe@waseda.jp

was 23.6°C and relative humidity was 37%RH during the 110-min experimental period (Nishikawa *et al.*, 2003).

Table 1 Experimental conditions (Mean ± SD)

Condition	Air temperature (°C)	Mean radiant temperature(°C)	Relative humidity (%RH)	Air velocity (m/s)
Practice	28.2 ± 0.07	28.2 ± 0.08	50 ± 0.6	0.10 ± 0.10
Control	28.3 ± 0.10	28.2 ± 0.12	51 ± 0.6	0.10 ± 0.10
CAV	31.0 ± 0.19	31.0 ± 0.20	50 ± 0.6	1.44 ± 1.33
PAV	31.2 ± 0.13	31.2 ± 0.14	49 ± 0.6	1.82 ± 1.71

SUBJECTIVE SENSATION

High Temperature

The results of the whole body thermal sensation vote, comfort sensation vote, thermal acceptability and sweating sensation vote are shown in Table 2. ASHRAE and Gagge scales were applied. In the 25.5°C condition, the average value of thermal sensation vote and sweating sensation vote of female subjects were significantly lower than that of male subjects ($p < 0.01$).

Air Velocity

The average value of thermal sensation vote, comfort sensation vote, thermal acceptability and sweating sensation vote are shown in Table 3. There was no significant difference between CAV and PAV for these parameters. The acceptability of air velocity of PAV was significantly higher than that of CAV after resting sedentary, text typing task and PAB test 2 (after resting, after PAB test 2, $p < 0.05$; after text typing test $p < 0.01$).

Lighting

Results of subjective votes on light environments are shown in Table 4. The value of 'Brightness' was higher under 800 lx than that at 3 lx. Subjects claimed darkness under 3 lx conditions. The value of 'Desire for brightness' was higher under 3 lx than at 800 lx. Subjects accepted 800 lx conditions about the light environment. On the other hand, they did not accept 3 lx.

Table 2 Subjective vote about thermal environment (Mean ± SD)

		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

Table 3 Votes on thermal environment

	Thermal sensation	Comfort sensation	Thermal acceptability	Sweating sensation
Practice	1.9 ± 0.8	–1.5 ± 0.6	–0.1 ± 0.7	1.3 ± 0.5
Control	1.5 ± 0.7	–1.2 ± 0.6	0.0 ± 0.4	1.0 ± 0.8
CAV	0.9 ± 1.1	–1.0 ± 0.7	0.0 ± 0.5	0.9 ± 0.5
PAV	0.7 ± 1.2	–1.0 ± 0.6	0.2 ± 0.5	0.8 ± 0.4

Table 4. 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

RESULTS OF TASK PERFORMANCE

Moderate High Temperature

For female subjects, there was no significant difference in the performance of all computer tasks among environmental conditions. For male subjects, there was no significant difference in the performance tests except a few cases. It was reported that performance of mental tasks has been generally unaffected by heat (Pepler and Warner, 1968; Sundstrom, 1987). Previous reviews of the impact of the thermal environment upon performance of mental tasks generally conclude that productivity research is somewhat confusing because the results are sometimes conflicting.

(Lorsch and Abdou, 1994; CIBSE Technical Memoranda, 1999). In this study, the effects of thermal environment on task performance were also contradictory between the task types, same as in previous findings.

Air Velocity

Interval production task was evaluated by subjective estimated time of 1 s. The other task performances were evaluated by using the number of the correct answer per 1 min. There was no significant difference of task performance between PAV and CAV.

Lighting

The performance of addition tasks is shown in Figure 1. Surprisingly, difference between 800 and 3 lx was not significant.

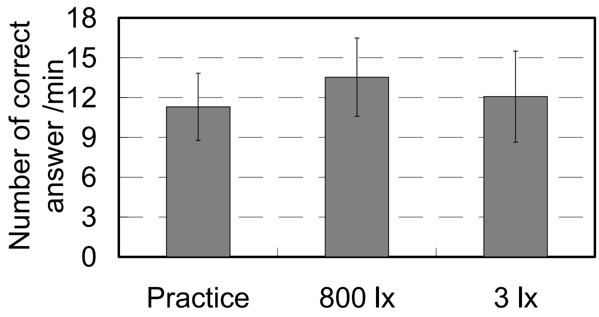


Figure 1. Performance of addition task

EVALUATION OF SUBJECTIVE SYMPTOMS OF FATIGUE

To evaluate the feeling of fatigue, subjects filled in the sheets of 'Evaluation of Subjective Symptoms of Fatigue'. It consists of three categories; group I consists of 10 terms about 'drowsiness and dullness', group II consists of 10 terms about 'difficulty in concentration' and group III consists of 10 terms about 'projection of physical disintegration'. Three categories are shown in Table 5. By the order of their rates, three types of fatigue feeling were estimated (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'.

Table 5 Three categories of subjective symptoms of fatigue

I	II	III
Feel heavy in the head	Feel difficulty in thinking	Have a headache
Get tired of the whole body	Become weary of talking	Feel stiff in the shoulders
Get tired of the legs	Become nervous	Feel a pain in the back
Give a yawn	Unable to concentrate attention	Feel opressed 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	Have a dizziness
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

Moderate High Temperature

General rate of complaints before the task at 33°C were the highest. The order among three categories of the subjective symptoms of fatigue is shown in Table 6. Before the task, at 25 and 28°C, the order of fatigue symptoms was I > III > II, which was grouped as 'General pattern of fatigue'. On the other hand, under 33°C conditions, it was I > II > III, which was grouped as 'Typical pattern of fatigue for mental work and overnight duty'. After the task, in male subjects, the order of the groups was I > II > III, which was grouped as 'Typical pattern of fatigue for mental work and overnight duty' in all conditions. In female subjects, it was I > III > II at 25 and 28°C conditions, and I > II > III at the 33°C condition. The subjects complaining of the feeling of mental fatigue was the highest at operative temperature of 33°C.

Table 6 The order among three categories of the subjective symptoms of fatigue

Male / female	Conditions	Group I (%)	Group II (%)	Group III (%)	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

Air Velocity

The general rate of complaints and the order among three categories of the subjective symptoms of fatigue are shown in Table 7. The general rate of complaints of PAV were the lowest in all conditions. In PAV condition, their order was I > III > II, and it was categorized as 'General pattern of fatigue'. On the other hand, in Practice, Control and CAV conditions, it was I > II > III and they were categorized as 'Typical pattern of fatigue for mental work and overnight duty'. According to the evaluation of subjective symptoms of fatigue, the subjects expressed more complaints of mental fatigue more at CAV than that at PAV. It was found that providing individual control of air velocity reduced the feeling of mental fatigue.

Table 7 The order among three categories of the subjective symptoms of fatigue

Conditions	General rate of complaints (%)	Group I (%)	Group II (%)	Group III (%)	The order among three categories
Practice	16.3	20.5	15.7	12.9	I > II > III
Control	13.2	17.2	11.5	10.8	I > II > III
CAV	14.4	17.8	14.1	11.3	I > II > III
PAV	10.0	15.6	4.6	9.9	I > III > II

Lighting

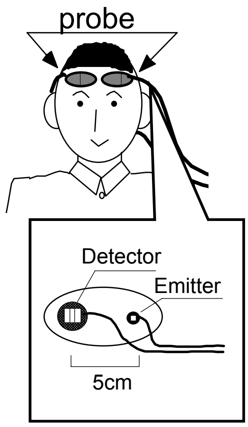
The general rate of complaints under 3 lx conditions was higher than at 800 lx conditions. Also, the rate of complaints increased after tasks under any conditions. The order among three categories of the subjective symptoms of fatigue is shown in Table 8. Under 800 lx conditions, before and after tasks, the order among three categories was I > III > II, which 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, which is grouped as 'Typical pattern of fatigue for mental work and overnight duty'. The subjects complaining of the feeling of mental fatigue was the highest after all tasks under 3 lx conditions. These results imply that the subjects felt mental fatigue strongly against the tasks under 3 lx.

Table 8 General rate of complaints and the order among 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
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

EVALUATION BY NEAR-INFRARED SPECTROSCOPY

To evaluate the changes in cerebral blood oxygenation during task by near-infrared spectroscopy (NIRS), experiments were conducted with six college-going age subjects participated in the experiment. Chamber was conditioned at operative temperatures of 25 and 33°C. In addition, a practice session at operative temperature of 25°C was conducted. The probe of a near-infrared spectrometer (NIRO-300) is shown in Figure 2. Near-infrared light was produced by laser diodes and carried to the tissue via optical fibres. The changes in concentration of total haemoglobin were measured: Δtotal Hb $=\Delta O_2Hb+\Delta HHb$. The increase rates of ΔO_2Hb and Δtotal Hb at left side head under 33°C was significantly higher than those under at 25°C in positioning, text typing and PAB test. There was no significant difference in ΔHHb between 33 and 25°C. Changes in the concentration of total haemoglobin are shown in Figure 3. Previous study reported that increments of ΔO_2Hb and Δtotal Hb, and decrements of ΔHHb were the typical findings by NIRS during the brain activation and mental work. The results at 33°C conditions indicated the typical cerebral blood oxygenation during the brain activation and mental work as in the previous study.



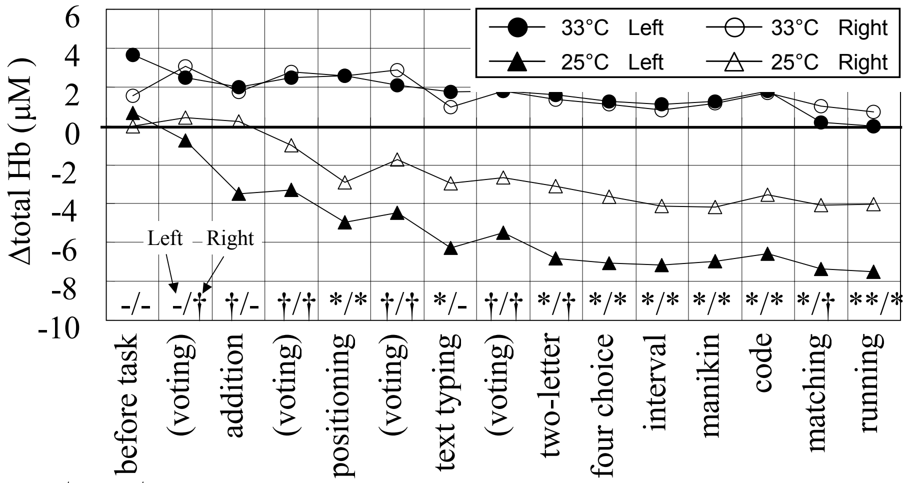
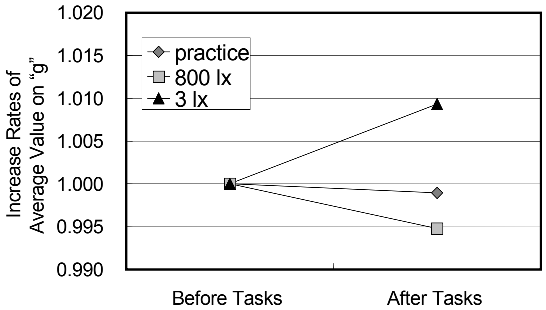


Figure 2 Near-infrared spectrometer.

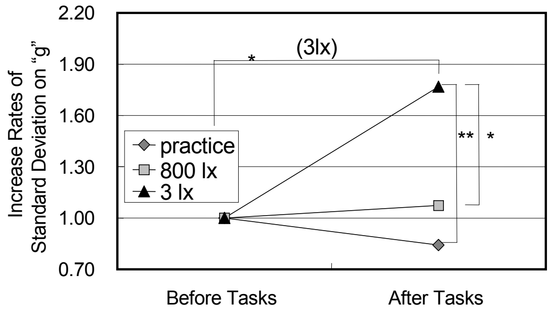
Figure 3 The changes in the concentration of total haemoglobin during each task. About each left and right side of cerebral haemoglobin concentration, the results of paired t-test between 25 and 33°C during each task are shown (–, not significant, †, $p < 0.1$; *, $p < 0.05$; **, $p < 0.01$).

EVALUATION OF PHYSICAL FATIGUE BY HUMAN VOICES

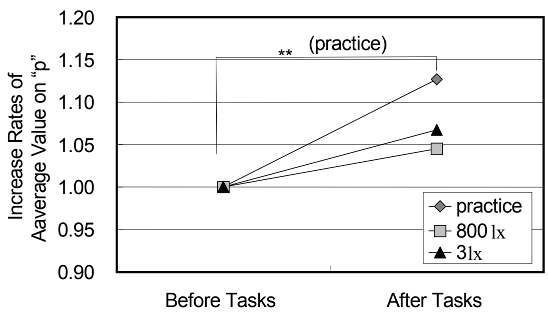
The Lyapunov exponents before and after three tasks were analysed (Shiomi and Hirose, 2000). The increase rates of the standard deviation on ‘g’ and ‘p’ at 3 lx were significantly higher than those at 800 lx ($p < 0.05$). The increase in rates of the standard deviation on ‘g’ and ‘p’ after tasks were also significantly higher than those before tasks ($p < 0.05$); see Figure 4. It was clear from subjective vote on symptoms of fatigue that subjects felt fatigue after tasks at 3 lx. As a result, the increased rates of standard deviation within subjects of the Lyapunov exponents on ‘g’ and ‘p’ have the possibility of evaluating fatigue.



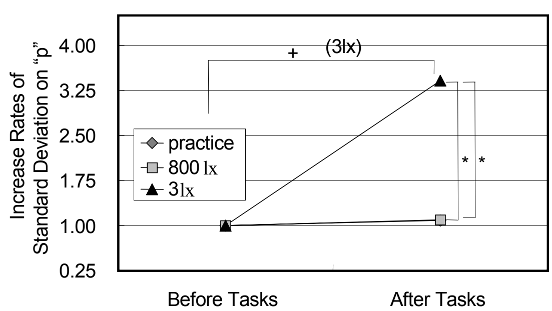
Increase in rates of average value on ‘g’



Increase in rates of standard deviation on ‘g’



Increase in rates of average value on ‘p’



Increase rates of standard deviation on ‘p’

Figure 4 Changes in both the average value and the standard deviation of the Lyapunov exponents on ‘g’ and ‘p’ (+, $p < 0.1$; *, $p < 0.05$; **, $p < 0.01$).

CONCLUSIONS

Effects of productivity for three environmental factors were investigated. Evaluation of not only performance, but also the negative aspect, namely fatigue is important to evaluate productivity. An objective method to evaluate fatigue is also introduced here.

ACKNOWLEDGEMENTS
The author wishes to express thanks to Ms N. Nishihara for her assistance. This study was partially funded by the Grant-in-Aid for Scientific Research (A) of the JSPS (No.14205085).

REFERENCES

CIBSE (1999). Environmental factors affecting office worker performance: a review of evidence *CIBSE Technical Memoranda TM24*. Windsor, Berks: Reedprint Limited

Lorsch, H.G. and Abdou, O.A. (1994). The impact of the indoor environment on occupant productivity—Part 2. Effects of temperature. *ASHRAE Transactions* **100** (2), 895–901.

Nishihara, N. and Tanabe, S. (2003). Individual control of air velocity for increasing productivity. *Healthy Buildings 2003 Conference Proceedings* (in press).

Nishihara, N., Yamamoto, Y. and Tanabe, S. (2002). Effect of thermal environment on productivity evaluated by task performances, fatigue feelings and cerebral blood oxygenation changes. *Indoor Air 2002 Conference Proceedings*, pp. 828–833.

Nishikawa, M., Nishihara, N., Hirose, S. and Tanabe, S. (2003). A new method for evaluating productivity and fatigue with human voice under 800 lx and 3 lx lighting conditions. *Healthy Buildings 2003 Conference Proceedings* (in press).

Parsons, K. (1993). *Human Thermal Environment*, pp. 199–217. London, UK: Taylor & Francis.

Pepler, R.D. and Warner, R.E. (1968). Temperature and learning: an experimental study. *ASHRAE Transactions* **74** (2), 211–224.

Shiomi, K. and Hirose, S. (2000). Fatigue and drowsiness predictor for pilots and air traffic controllers. *45th Annual ATCA Conference*.

Sundstrom, E. (1987). Work environments: offices and factories. In Stokols, D. and Altman, I. (eds), *Handbook of Environmental Psychology*, Vol. 1, pp. 733–782. New York: John Wiley.

Wargocki, P., Wyon, D.P., Sundell, J., Clausen, G. and Fanger, P.O. (2000). The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air* **10**, 222–236.

Wyon, D.P. (1986). The effects of indoor climate on productivity and performance: a review. *WS and Energy* **3**, 59–65.

Yoshitake, H. (1973). *Occupational Fatigue—Approach from Subjective Symptom*. Tokyo, Japan: The Institute for Science of Labor (in Japanese).