Productivity, Energy, and Economics in Modern Offices

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SUMMARY

To promote the effort for energy conservation, it is also important to estimate the indoor environmental quality (IEQ) from the aspect of office worker’s productivity. A conceptual diagram for the evaluation of the effect of IEQ on productivity was proposed. The results from subjective experiments of short term showed that human responses, such as fatigue, cerebral blood flow, sensation to the environment and SBS symptoms, were important for the evaluation of productivity. The results from a subjective experiment of long term exposure revealed the relationship that performance decreased with the increase in the level of fatigue. The results from another subjective experiment showed that the subjects performed well when they were satisfied with the IEQ. A survey in call-center showed the decline in performance in warmer environment. Economical and global environmental impacts from the modification of cooling temperature settings in office were also discussed.

INTRODUCTION

Productivity in general is defined as the quotient of Output over Input. The economic index for expressing the cost effectiveness of the improvement of IEQ can be proposed by dividing the benefits (Output) obtained through the improvement of IEQ by the cost factors (Input) for the improvement. Input-side cost factors, e.g. expenditure of the facility investment, are rather simple to estimate. Output-side benefits, on the other hand, were calculated by converting the quantified performance changes in terms of salaries [1], [2]. However, the output-side factors, e.g. the performance of the workers, are difficult to quantify in most cases, because the factors include intellectual activities, which can be influenced by psychological factors such as arousal level and motivation, as pointed out by McIntyre [3]. From the results of our laboratory experiments [4], [5], the effects of indoor environment were observed in human responses, such as fatigue, cerebral blood flow, sensation to the environment and SBS symptoms, even when there was no significant change in the performance. The performance would eventually decrease, in hypothesis, when workers were tired or dissatisfied with the environment.

A conceptual diagram for the evaluation of the effect of IEQ on productivity is proposed as shown in Figure 1. As indicated above, human responses are considered to be the intermediate factors affecting the performance of the workers by the indoor environment, and hence included in the conceptual diagram. In this paper, several evidences from subjective experiments and a field survey to explain the diagram. Also, an example of the evaluation of productivity was shown on the modification of cooling temperature settings in a typical office in Japan.
EFFECT OF HIGH TEMPERATURE ON TASK PERFORMANCE AND FATIGUE (SHORT EXPOSURE)

Method
To study the effect of moderately high temperature on task performance and fatigue, a subjective experiment was conducted in a climate chamber [6]. College-age subjects, 20 males and 20 females, participated in the experiment. The chamber was conditioned at operative temperatures of 25.5°C, 28.0°C, and 33.0°C with still air. Previous to these three conditions, a practice session at an operative temperature of 25.5°C was conducted. Relative humidity was controlled around 50%. Subjects wore a uniform with an insulation value of 0.76 clo. Task performance tests on computer were conducted for 1.5 hours.

The experimental procedure is shown in Figure 2. After entering the climate chamber, subjects waited in a sedentary position for 30 minutes, 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 minutes, the positioning test for 5 minutes, the text typing test for 5 minutes, and the Walter Reed Performance Assessment Battery test (PAB) [7] for about 15 minutes. After each test, an intermission of 5 minutes 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 minutes after entering the climate chamber as “before task” and after all computer tasks were finished, as “after task”.

Task Performance
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. The performance of addition task is shown in Figure 3. In this study, the effects of thermal environment on task performance were contradictory among the task types as in previous findings [8], [9]. It is difficult to evaluate the effect of thermal environment on productivity by measuring only task performance.

![Figure 3. Performance of addition task](image)

**Evaluation of Subjective Symptoms of Fatigue and Cerebral Blood Flow**

To evaluate the feeling of fatigue, subjects filled in the sheets of “Evaluation of Subjective Symptoms of Fatigue” [10]. It consists of three categories; I-group consists of 10 terms about “drowsiness and dullness”, II-group consists of 10 terms about “difficulty in concentration”, and III-group consists of 10 terms about “projection of physical disintegration”. The subjects complained of a feeling of mental fatigue and complained the most just being in the room with operative temperature of 33.0°C.

Previous studies reported that increase of $\Delta O_2 Hb$ and $\Delta total Hb$ and decrease of $\Delta HHb$ were the typical findings by NIRS during the brain activation and mental work [11], [12]. In another experiment, it was showed that there was no significant difference in task performances between 26.0°C and 33.5°C conditions, but the increase of $\Delta totalHb$ was higher at 33.5°C than that at 26.0°C [13]. Hot environments required more cerebral blood flow to maintain the same level of task performance.

**EFFECT OF HIGH TEMPERATURE ON TASK PERFORMANCE AND FATIGUE (LONG EXPOSURE)**

**Method**

To study the relationship between the task performance decrement and the work time, six hours of subjective experiment was conducted in a climatic chamber [14]. Fifteen college-age male subjects participated in this experiment. The conditions were set by the combination of operative temperature in the chamber and the amount of clothing insulations as: 25.0°C with 1.0 clo; 28.0°C with 1.0 clo; 28.0°C with 0.7 clo. Previous to these experimental conditions, a practice at 25.0°C with 1.0 clo condition was conducted.

The experimental procedure is shown in Figure 4. After entering the chamber, the subjects waited for 30 minutes in sedentary position, and then reported their first thermal sensation in the chamber and their feeling of fatigue. Subjects were then assigned nine sessions of addition tasks. In each session, the subjects worked for 30 minutes on the task and they reported thermal sensation, their feeling of fatigue, their evaluation of the task load in 5 minutes.
Figure 4. Experimental procedure

**Task Performance**

Figure 5 shows the result of normalized performance. The normalized performance did not change significantly at 25.0°C with 1.0 clo condition over the time. However, the performance was significantly lower after sixth session (each p<0.05) at 28.0°C with 1.0 clo condition. Also, the performance was significantly lower after the third session (each p<0.05) at 28.0°C with 0.7 clo.

**Fatigue and Performance**

To determine the relationship between the level of fatigue and performance, the results of “Evaluation of Subjective Symptoms of Fatigue” were analyzed. Personal rates of complaints of fatigue, which were the general rates of complaints of fatigue for individual in each environmental condition excluding the results of practice session, were calculated. Figure 6 shows the correlation of personal rate of complaints of fatigue and normalized performance. It showed strong relationship that performance decreased with the increase in the level of fatigue. The correlation coefficient was -0.76. From the regression equation obtained from the results, increase in 10% of fatigue corresponds to the decrement in performance by 1.7%. The result showed the link from the fatigue of the occupants to the performance of them. It implies that evaluating fatigue is useful for estimating the effect of indoor environment on performance in offices and in experiments.

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Figure 5. Result of normalized performance  
Figure 6. Correlation of the personal rate of complaints of fatigue and normalized performance

**EFFECTS OF SATISFACTION WITH IEQ ON PERFORMANCE**

**Method**

A subjective experiment was conducted in a climatic chamber to evaluate the effects of improvement of IEQ on occupant’s performance [15]. The chamber was conditioned with the combination of: operative temperatures of 25°C or 28°C, illuminance of 750lx or 400lx and with or without traffic noise. Eight conditions were named as “Control(28°C, 400lx, with traffic noise)”, “T(25°C, 400lx, with traffic noise)”, “N(28°C, 400lx, without traffic noise)”, “L(28°C, 750lx, with traffic noise)”, “TN(25°C, 400lx, without traffic noise)”, “TL(25°C, 750lx, with traffic noise)”, “NL(28°C, 750lx, without traffic noise)” and “TNL(25°C, 750lx, without traffic noise)”. 
The experimental procedure is shown in Figure 7. Duration of the experiment lasted for 210 minutes. First, subjects entered the climatic chamber, and they voted satisfaction with indoor environment and fatigue on a PC screen. They rested in a sedentary position for 45 minutes to adopt themselves to the environment. Then, they performed thirty-minutes of multiplication task four times, and voted satisfaction with indoor environment and fatigue before and after the tasks. They were asked to answer predicted-performance-vote at the end of the day.

Figure 7. Experimental procedure

Relation between Satisfaction with Indoor Environment and Performance
Subjects voted their satisfaction with indoor environment six times a day, before and after each session of resting and task. The results of the votes of satisfaction with indoor environment are shown in Figure 8. They were satisfied with environments of TN and TNL, and dissatisfied with those of all other conditions.

To evaluate how much satisfaction with indoor environment affects task performance, the relationship between satisfaction with indoor environment and the Z-score of multiplication task were examined. The data set of satisfaction with indoor environment by the interval of 0.2 was averaged and corresponding Z-score was also averaged. The relationships between satisfaction with indoor environment and the Z-score are shown in Figure 9. The Z-score was related to subjects’ satisfaction with indoor environment (r=0.43). The results from the experiment showed that the subjects performed well when they were satisfied with the IEQ. To promote increase of productivity in the office, it is effective to build up the environment providing high occupants’ satisfaction.

Figure 8. Satisfaction with Indoor Environment
Figure 9. Relationship between Satisfaction with Indoor Environment and Performance

FIELD SURVEY IN CALL CENTER

Method
Data in a call center was collected for one year [16]. Indoor air temperature, humidity, lighting, and CO₂ concentration were monitored. Measurement was conducted from February 18, 2004 to February 1, 2005. Figure 10 shows the interior of call center. Call data of 13,169 were collected in total. This call center is performing guidance and consultation for customers, and technical support. Although the number of communicators changes with a day and time,
total number of workers is about 70-120 persons/day in general. Business-hours of a call center are 8:45-19:00 from Monday to Saturday. Air-conditioning is operated from 8:00 to 20:00. Detailed research result is published by Kobayashi et al., see reference [16].

**Call Response Rate**

The relationship between indoor air temperature and the average call-response rate is shown in Figure 11. A linear regression model weighted by the number of relevant operators was obtained with the correlation coefficient of -0.69. Based on the regression model, the increase in air temperature by 1.0°C is relevant to the decrease in call response rate by 0.15 calls/h. In particular, increasing indoor air temperature by 1.0°C from 25.0 to 26.0°C would result the decrement in call response rate from 7.79 to 7.64 calls/h, which is 1.9% loss in performance. Seppänen et al. reported that 1.0°C of room air temperature rise is equivalent to decline in 2% of working performance [17]. The result of this research agreed quite well with the model of Seppänen. The average arrival telephone calls time per response number of cases, average receivable time, and the average desk work time were performed stable for whole period. Call-response rate was adopted as an index to evaluate the worker performance. For long period field study indoor air temperature has effects on workers’ productivity.

**ECONOMICAL AND GLOBAL ENVIRONMENTAL IMPACTS FROM THE MODIFICATION OF COOLING TEMPERATURE SETTINGS IN OFFICE**

The effects of the modification of the cooling temperature settings were evaluated and analyzed. The primary energy consumption of the typical office building in Japan, Building K, was calculated by the Building Energy Consumption Simulator (BECS), which is commonly used in Japan for the Energy-Saving Law. The conditions for the simulation are shown in Figure 12. The temperature settings of the air-conditioning system changed by the seasons as: spring and autumn at 24°C (April, May, October, and November); summer at 26°C (June to September); and winter at 22°C (December to March).

Figure 10. Interior view of a call center

Figure 11. Relationship between indoor air temperature and the average response number of cases

Figure 12. Conditions for the energy consumption simulation. (a) typical floor plan for the Building K, and (b) description of the Building K
The cases studied were: the standard operation of the office buildings as Case-26°C; and the modification of cooling temperature settings during summer for two Centigrade, at 28°C, as Case-28°C. Same air-conditioning systems were assumed to be operated in both cases, and the simulations were conducted over a year. From the results, the primary energy consumption was 1180.5MJ/m²/year for Case-26°C and was 1161.2MJ/m²/year for Case-28°C. The difference between the two cases was only 19.3MJ/m²/year (-1.64%), because chillers were not always operated at the rated point.

The effects of the modification of the cooling temperature settings were evaluated in terms of: (I) the benefit by the reduction in the running cost (yen/m²/year), (II) the cost by the performance changes (yen/m²/year), and (III) the reduction in the amount of emission of carbon dioxide (kg-CO₂/m²/year). They were calculated with the following three equations:

\[
\begin{align*}
(I) &= \Delta E_{AC} \times M_E, \\
(II) &= k_{summer} \times M_p \div S_p \times \Delta P, \\
(III) &= k_{CO2} \times \Delta E_{AC},
\end{align*}
\]

where, \(\Delta E_{AC}\) is the reduction in energy consumption (kWh/m²/year), \(M_E\) is the price of energy (yen/kWh), \(k_{summer}\) is the number of months in summer to year (=4/12), \(M_p\) is the average salary (≈4 million yen/person/year [18]), \(S_p\) is the space per person (=10m²/person), \(\Delta P\) is the change in performance (%), and \(k_{CO2}\) is the CO₂ emission rate for a thermal power plant (=0.378kg-CO₂/kWh). The building facility was assumed to be operated by electricity from a thermal power plant, whose conversion factors are 9MJ/kWh [19] and 11.08yen/kWh in Tokyo. The change in performance was cited from the result of the survey, 1.9%/°C.

The results of the cost analysis and the reduction in carbon dioxide emission when the cooling temperature settings were modified by 2°C in the Building K are shown in Table 1. The net profit by the modification was -5043 yen/m²/year, while the reduction in CO₂ emission was 0.81kg-CO₂/m²/year. It was suggested from the results that (I) the benefit by the reduction in the running cost and (III) the reduction of the CO₂ emission would be minimal compared to the possible cost generated by the performance decrement. The reduction in the emission of greenhouse gases is essential for the world wide concern of the global warming issue; however, it is also important to give considerations on productivity for the measures in offices.

Table 1. The results of the cost analysis and reduction in carbon dioxide emission by modifying the temperature settings by 2°C

<table>
<thead>
<tr>
<th></th>
<th>(I) Reduction in running cost</th>
<th>(II) Cost by performance change</th>
<th>(III) Reduction in CO₂ emission</th>
<th>(I)-(II) net profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.8 yen/m²/year</td>
<td>5067 yen/m²/year</td>
<td>0.81kg-CO₂/m²/year</td>
<td>-5043 yen/m²/year</td>
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**CONCLUSION**

1) A conceptual diagram for the evaluation of the effect of indoor environmental quality on productivity was proposed.

2) The results from subjective experiments of short term showed that human responses, such as fatigue, cerebral blood flow, sensation to the environment and SBS symptoms, were important for the evaluation of productivity.

3) The results from a subjective experiment of long term exposure revealed the relationship that performance decreased with the increase in the level of fatigue.

4) The results from another subjective experiment showed that the subjects performed well when they were satisfied with the IEQ.

5) A survey in call-center showed the decline in performance in warmer environment.
6) From the simulation on the economical and global environmental impacts for the modification of cooling temperature settings in an office, it was suggested from the results that the benefit by the reduction in the running cost and the reduction of the CO₂ emission would be minimal compared to the possible cost generated by the performance decrement.

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