MONITORING CEREBRAL BLOOD FLOW FOR OBJECTIVE EVALUATION OF RELATIONSHIP PRODUCTIVITY AND THERMAL ENVIRONMENT

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ABSTRACT
It is difficult to evaluate the effect of indoor environmental quality on productivity by measuring only task performance. In this study, the monitoring of cerebral blood flow during task by Near Infrared Spectroscopy is introduced as one of the objective evaluation methods of workers’ human response that are factors affecting task performance. The results of three subjective experiments showed that monitoring cerebral blood flow can be applied to evaluation of mental demand level they need to do tasks. The higher mental demand was required, the more the left side of Δtotal hemoglobin concentration became. The results of the subjective experiments in moderately hot environment show that the mental demand level to maintain their task performance was higher in hotter environment than that in thermal neutral environment.

KEYWORDS
Productivity; Thermal environment; Cerebral blood flow; Mental demand level, Task performance

INTRODUCTION
Productivity is defined as the extent to which activities have provided performance in terms of system goals (Parsons 1993) and generally defined as the ratio of Output per Input. Many experimental studies have been mainly focused on task performance as output side index to estimate the effect of indoor environmental quality (IEQ) on productivity. The evidence of the relationship between indoor air temperature and performance becomes stronger (Wargocki and Seppänen 2006) and the model that suggested a reduction of performance by about 1% for every 1°C (reduction / increase) of temperature from the reference temperature of 22°C (Seppänen 2006). On the other hand, psychological factors such as arousal level or motivation level have larger impact on results of task performance (McIntyre, 1980). Previous reviews of the impact of 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).

It is difficult to evaluate the effect of indoor environmental quality on productivity by measuring only task performance. For example, if workers’ motivation is high, increasing air temperature and reducing light intensity from the optimal conditions did not affect the task performance in our previous studies (Nishihara and Tanabe 2003, Nishikawa et al. 2003). On the other hand, if subjects maintained their task performance under the poor indoor environmental quality we found that their human responses that related to the task performance such as fatigue level or mental demand was affected by indoor environmental quality (Tanabe and Nishihara 2004). To evaluate effect of thermal environment on productivity, it is necessary to measure not only task performance but also the degree of their mental demand and fatigue during the task.

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In this study, the monitoring of cerebral blood flow during task is introduced as one of the objective evaluation methods of workers’ human response that are factors affecting task performance. Three experiments were reviewed and discussed in this paper.

**NEAR INFRARED SPECTROSCOPY**

The near infrared spectrometer (NIRO-300, Hamamatsu Photonics) was shown in Figure 1. NIRO-300 was used to measure cerebral blood oxygenation changes during exposure. 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 value of transmitted light intensities were recorded every second. Sampling rate was 2,000 times per second. Changes in the concentration of the chromophores oxygenated hemoglobin \(\Delta\text{oxy-Hb}\) and deoxyhemoglobin \(\Delta\text{deoxy-Hb}\) were calculated by Modified Beer-Lambert equation in \(\mu\text{M} = 10^{-6} \text{ mol units}\) (Deply et al. 1988). The changes in concentration of total hemoglobin were calculated as index of change rate of cerebral blood flow: \(\Delta\text{total Hb} = \Delta\text{oxy-Hb} + \Delta\text{deoxy-Hb}\).

Previous studies reported that increase of \(\Delta\text{oxy-Hb}\) and \(\Delta\text{total Hb}\) and decrease of \(\Delta\text{deoxy-Hb}\) were the typical findings by NIRS during the brain activation and mental work (Villringer et al. 1993, Kido 1995). The mechanism was explained as follows (Sakatani 2002): brain blood is necessary for active of brain but there are few stocks of glucose and \(\text{O}_2\) in brain. So, it is necessary to supply them by blood flow. The \(\Delta\text{oxy-Hb}\) and \(\Delta\text{total Hb}\) becomes higher in brain activity. The consumption of \(\text{O}_2\) in brain activity is much smaller than the increase rate of cerebral blood flow. So, \(\Delta\text{deoxy-Hb}\) becomes relatively lower in brain activity.

From the studies of split-brain, left brain is more dominant for linguistic abilities, calculations, math and logical abilities where right-brain is more dominant for spatial ability (Oono 1996), and it was also reported that most right handed people’s language center is on the left side of brain (Kubota 1982, Sakano 1982).

![Figure 1 Near infrared spectrometer](image)

**EXPERIMENT 1: MENTAL DEMAND LEVEL AND CEREBRAL BLOOD FLOW**

**Purpose**

In this experiment (Nishihara and Tanabe 2004), the mental demand level during task was focused. It is necessary for evaluation of task performance to focus on not only task performance but also how much mental effort they need to do task. It was still unknown if cerebral blood oxygenation changes might be applied to the evaluation of the degree of mental demand during task. In this study, relationship between the changes in cerebral blood oxygenation and mental demand level was evaluated by subjective experiments.
Methods
Six right-handed male subjects of college-going age participated in the experiments. Four different difficulty levels of tasks were given to the subjects: single-digit addition, double-digit multiplication, triple-digit addition, and triple-digit multiplication. The experimental procedure is shown in Figure 2. After entering the experimental room and setting sensors, subjects stayed there in a sedentary state for 5 min. And then, subjects were asked to do single-digit addition task for 5 minutes as many as possible and they voted on NASA-TLX (National Aeronautics and Space Administration Task Load Index)(Hart and Staveland 1988). The Japanese version of NASA-TLX (Miyake and Kumashiro 1993) was used for experiments. After that, subjects were asked to do the other three types of tasks; double-digit multiplication, triple-digit addition, and triple-digit multiplication. Subjects experienced these three tasks in balanced order among them. After each test, the subjects were asked to record NASA-TLX and subjective difficulty level of each task comparing to the level of single-digit addition task.

Results
It was evaluated that the more difficult task types to solve, the more oxygenated hemoglobin and total hemoglobin concentration were needed. There was a significant correlation between subjective value of mental demand for tasks and the left side of Δ total hemoglobin concentration. The change rate of total hemoglobin during each task is shown in Figure 3. 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 Figure 4. There was a significant correlation between the subjective value of mental demand for tasks and the left side Δtotal Hb. Monitoring cerebral blood oxygenation changes could be applied to the evaluation of the index of the degree of mental demand to perform the task.
EXPERIMENT 2: MODERATELY HOT ENVIRONMENT AND CEREBRAL BLOOD FLOW

Purpose
To evaluate the effect of moderately hot environment on workers’ productivity, subjective experiment was conducted (Nishihara and Tanabe 2005). Cerebral blood flow was measured by near infrared spectroscopy as an index of mental demand.

Methods
Twelve right-handed male subjects of college-going age were exposed in a climatic chamber to two operative temperature levels of 26.0°C and 33.5°C. Subjects experienced these two conditions in balanced order. Before these two conditions, they participated in a practice session under operative temperature of 26.0°C at the first time. In this study, in order to increase their motivation to the same level, they were informed that the top 6 performers of the computer tasks could earn one hour’s worth of bonus. Therefore, it could be assumed that subjects were highly motivated. Experimental procedure is shown in Figure 8. After adaptation to the thermal environment for 50 minutes, three types of calculation task (single digit addition, triple digit addition and triple digit multiplication) were assigned to subjects. To measure the cerebral blood flow during rest (baseline), subjects were asked to close their eyes, “clear their mind” and relax for 2 min just after entering chamber, after adaptation for 50 minutes and after tasks.

Results
Subjects evaluated the environment in 33.5°C as hotter and stuffier of air compared to that at 26.0°C. There were no significant differences in task performances between 26.0°C and 33.5°C conditions. According to the evaluation of subjective symptoms of fatigue, the subjects complained of the feeling of mental fatigue more at operative temperature of 33.5°C than 26.0°C. The results of $\Delta$totalHb that were calculated based on the value after adaptation were shown in Figure 6. During both triple digit addition and triple digit multiplication, the increase of $\Delta$totalHb was significantly higher at 33.5°C than that at 26°C (triple digit addition: $p<0.02$, triple digit multiplication: $p<0.04$). At 26°C condition, the increase of $\Delta$totalHb during triple digit multiplication was significantly higher than that during triple digit addition ($p<0.03$). At 33.5°C condition, there was no significant difference between triple digit addition and multiplication. There was no significant difference of the change rate during adaptation for 50 minutes and after tasks between 26°C and 33.5°C.
EXPERIMENT 3: LONG TIME EXPOSURE IN MODERATELY HOT ENVIRONMENT AND CEREBRAL BLOOD FLOW

Purpose
In above two experiments, the task performing time was only 5 minutes per each task and short. In this experiments, longer tasks were imposed to subjects. A subjective experiment was conducted in a climatic chamber that was conditioned at the operative temperatures of 25.5°C, 28.5°C or 31.5°C (Nishihara et al. 2007).

Methods
Twelve right-handed male subjects of college-going age were exposed in a climatic chamber to three operative temperature levels of 25.5°C, 28.5°C and 31.5°C for 170 minutes. Figure 7 shows the experimental procedure. Three sessions of the triple digit multiplication tasks on paper for 30 minutes/session were assigned to subjects. Cerebral blood flow was measured during exposure by NIRO 300. To measure the cerebral blood flow during rest (baseline), subjects were asked to close their eyes, “clear their mind” and relax for 2 min just after entering chamber, after adaptation for 54 minutes and after each task sessions.

Figure 7 Experimental procedure.
Results
The task performance for each subject was evaluated by his z-score as a normalized performance. The data set of RTLX by the interval of 5 was averaged and corresponding z-score was also averaged. The relationships between RTLX and Δ total hemoglobin concentration are shown in Figure 8. The correlation between RTLX and Δ total hemoglobin concentration was observed ($r = 0.65$).

In this study, there were no significant differences of RTLX and Δ total hemoglobin concentration between thermal environmental conditions. However, some significant differences of task performance between thermal environmental conditions were observed. In Task 3, the z-score in 25.5°C was significantly higher than that of 28.5°C and 31.5°C ($p<0.05$). In 31.5°C, there were tendencies that task performances fell from Task 1 to Task 2 and Task 3 ($p<0.1$).

DISCUSSIONS
There were significant correlations between subjective mental demand level for tasks and the left side of Δ total hemoglobin concentration in Experiment 1 and Experiment 3. In Experiment 2, at 26°C condition, the increase of ΔtotalHb during triple digit multiplication was significantly higher than that during triple digit addition. These results show that tasks that needed higher mental demand required more cerebral blood flow. Monitoring cerebral blood oxygenation changes might be applied to evaluation of the degree of mental effort they need to do tasks.

In Experiment 2 whose performing task time was 5 minutes/each task, there were no significant differences in task performances between 26.0°C and 33.5°C conditions but during tasks the increase of ΔtotalHb was significantly higher at 33.5°C than that at 26.0°C. On the other hand, in Experiment 3 whose performing task was 90 minutes and longer than Experiment 2, there were no significant differences of RTLX and Δ total hemoglobin concentration between thermal environmental conditions, but some significant differences of task performance between thermal environmental conditions were observed. These results show that the mental demand level to maintain their task performance was higher in hotter environment than that in thermal neutral environment.

CONCLUSIONS
In this study, the monitoring of cerebral blood flow during task by Near Infrared Spectroscopy is introduced as one of the objective evaluation methods of workers’ human response that are factors affecting task performance. The results were the followings:
1) Tasks that needed higher mental demand required more cerebral blood flow, and the left side of

![Figure 8 RTLX and Δ total hemoglobin concentration](image-url)
Total hemoglobin concentration was higher. Monitoring cerebral blood oxygenation changes might be applied to evaluation of the mental demand level they need to do tasks.

2) The mental demand level to maintain their task performance was higher in hotter environment than that in thermal neutral environment.

3) To evaluate effect of indoor environmental quality on productivity, it is necessary to measure not only task performance but also human responses such as the degree of their mental demand during the task.

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