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The effects of air temperature on office workers' well-being, workload and productivity-evaluated with subjective ratings

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ABSTRACT

Productivity bears a close relationship to the indoor environmental quality (IEQ), but how to evaluate office worker's productivity remains to be a challenge for ergonomists. In this study, the effect of indoor air temperature (17 °C, 21 °C, and 28 °C) on productivity was investigated with 21 volunteered participants in the laboratory experiment. Participants performed computerized neurobehavioral tests during exposure in the lab; their physiological parameters including heart rate variation (HRV) and electroencephalograph (EEG) were also measured. Several subjective rating scales were used to tap participant's emotion, well-being, motivation and the workload imposed by tasks. It was found that the warm discomfort negatively affected participants' well-being and increased the ratio of low frequency (LF) to high frequency (HF) of HRV. In the moderately uncomfortable environment, the workload imposed by tasks increased and participants had to exert more effort to maintain their performance and they also had lower motivation to do work. The results indicate that thermal discomfort caused by high or low air temperature had negative influence on office workers' productivity and the subjective rating scales were useful supplements of neurobehavioral performance measures when evaluating the effects of IEQ on productivity.

1. Introduction

Studies (Roelofsen, 2002; Woods, 1989; Lorsch and Ossama, 1994) have shown that productivity bears a close relationship to the indoor environment quality (heat, cold, noise, light, etc.). However, how to assess the effect of indoor environment quality on productivity remains to be the major challenge for ergonomists. Until now there have been no standard procedures to measure office worker's productivity, therefore it has been difficult to persuade clients to accept the concept of a relationship between economic productivity benefits and indoor environment quality. A neurobehavioral approach had been proposed to systematically and quantitatively evaluate the effects of indoor environment quality on office worker's productivity by several neurobehavioral tests, which assessed four classes of neurobehavioral functions involved in office work, including perception, learning and memory, thinking, and executive functions (Lan et al., 2009a). In the previous laboratory study some neurobehavioral tests had been used to investigate the effect of air temperature on productivity for a very short time (about 30 min). It was found that motivated people could maintain high performance for a short time under adverse (hot or cold) environmental conditions. However, it is unclear why the participants could maintain their performance and whether it will happen in the routine office work environment. In this paper, several subjective ratings as well as physiological measurements were made to investigate the effects of thermal discomfort on office workers' productivity. The object was to investigate the effects of thermal discomfort on occupants' workload, emotion, well-being, and motivation, and also the relationship between these activities and their neurobehavioral performance.

2. Methodologies

The experiment was carried out in an ordinary but low-polluting office ($L \times W \times H = 6 \times 4 \times 5$ m), in which participants sat at seven workstations, each consisting of a table, a chair and a personal computer (Fig. 1). The office was illuminated with eight fluorescent lamps. The room temperature was controlled by an air-conditioner, which was able to adjust temperature from 16 °C to 32 °C.

2.1. Participants

Twenty-one volunteered participants (6 females and 15 males) were recruited for this experiment. They were recruited based on

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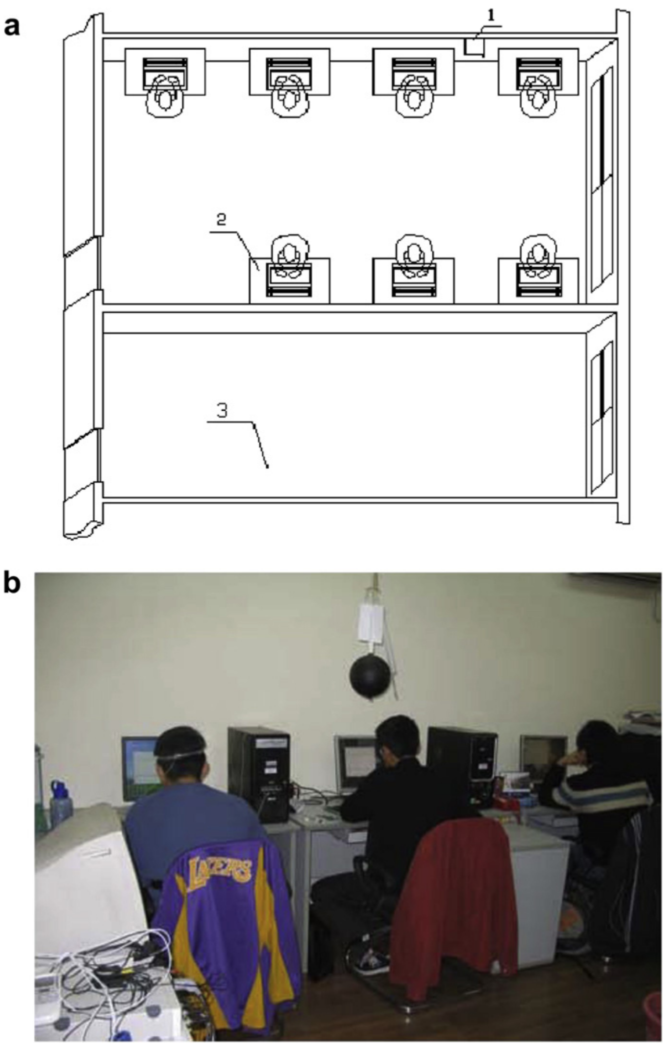

Fig. 1. (a) The layout of the experimental room (1) consisting of a table, a chair and a personal computer, (2) air conditioner and (3) waiting room; (b) a picture during the experiment.

the following criteria: familiarity with computer, impartiality to the office in which the study was carried out, and absence of chronic diseases, asthma, allergy, hay-fever and color blind. The participants were all students, aged 18–20 years ($\mu = 19$, $\sigma = \pm 1$). Participants were required to wear long-sleeved sweater, long thick trousers and long underwear top and bottoms, socks and shoes (an estimated clothing insulation value of 1.20 Clo, including the insulation of the chair). They were also asked to have a good rest at the night before the experiment. The participants were paid a salary for participation in the experiment at a fixed rate per hour. To increase their motivation and especially to encourage them to perform the tests seriously, bonus was paid depending on their performance. Participants all successfully completed experimental sessions.

All protocols were approved by the university's ethics committee and conformed to the guidelines contained within the Declaration of Helsinki. Verbal and written informed consent was obtained from participants before they participated in the experiment.

2.2. Measurements

2.2.1. Physical measurements

The temperature, relativity humidity and velocity of the air were measured. The mean radiant temperature was estimated from the globe temperature, which was measured using a 150 mm diameter black globe thermometer. The illuminant was measured with a digital luxmeter near each participant at the height of working face.

2.2.2. Physiological measurement

Participants' electrocardiogram (ECG) and electroencephalograph (EEG) were recorded by a Powerlab 8/30 system (AD Instruments, Australia) and the accessorial materials (e.g. adhesive pads, EEG or ECG electrodes, etc.). The standard bipolar limb leads (ML-1340) and adhesive ECG electrodes (MLA-1010) were linked to the data acquisition system through a dual bioamplifier (ML-135) for recording of ECG. The negative lead and the positive lead were clung to the right and left wrist, respectively, and the ground lead was clung to the right ankle. The EEG recordings were made using the bipolar method: a pair of electrode measured the difference in electrical potential (voltage) between the two positions above the brain, one being placed on the right side of the head (60% of distance from right ear to midpoint of the scalp), another being placed in the centre of the forehead, and a third electrode being put on the earlobe as a point of reference. There are three main spectral peaks of HRV distinguished in a spectrum calculate from 2 to 5 min ECG recordings: very low frequency (VLF: 0.003–0.04 Hz), low frequency (LF: 0.04–0.15 Hz), and high frequency (HF: 0.15–0.4 Hz) (Sayers, 1973). The ratio of low frequency to high frequency (LF/HF) is usually introduced to infer the sympathetic nervous system activity (Jaffe et al., 1993). Based on a 5-min record, the relative power of four EEG bands (δ-band EEG: 0.5–4 Hz; θ-band EEG: 4–8 Hz; α-band EEG: 8–14 Hz; β-band EEG: 14–35 Hz in frequency) and the value of LF/HF were calculated.

2.2.3. Performance measurement

Performance refers to the quality and quantity of finished task. Thirteen computerized neurobehavioral tests were used to evaluate participant's performance. The detailed description of these tests can be referred to Lan et al. (2009a) and Lan and Lian (2009b).

2.2.4. Subjective measurements

2.2.4.1. Thermal sensation votes. Thermal sensation votes (TSV) were cast on the ASHRAE/ISO 7-point thermal sensation scale (ASHRAE, 2001). Thermal comfort (TC) votes were cast on 5-point numerical scales – comfortable (0), slightly uncomfortable (1), uncomfortable (2), very uncomfortable (3), and extremely uncomfortable (4).

2.2.4.2. The Profile of Mood States. Participants' emotion was investigated with the *Profile of Mood States* (POMS). The POMS has been widely used as a research and clinical instrument. It consists of 65 adjectives describing feeling and moods that the participant may have experienced at that moment, or over the previous day, few days, or week, including key words such as unhappy, tense, careless, and cheerful (McNair et al., 1992). Each item is scored on a 5-point Likert-type scale ranging from 0 (not at all) to 4 (extremely) according to participants' responses. The POMS consists of six identifiable mood states: tension, depression, anger, vigor, fatigue, and confusion. A composite score, the total mood disturbance (TMD) score, is computed by summing each of the individual score for tension, depression, anxiety, fatigue and confusion, with vigor scores subtracted to indicate participant's total mood disturbance. The higher TMD score indicates higher negative mood.

2.2.4.3. Well-being and motivation. Motivation refers to the worker's mental drive and enthusiasm to carry out a work. If a person is reluctant to work, then no matter how accurately he can perform, the productivity should be deteriorated. Well-being indicates the physical and mental health of a worker. Unless a person feels a positive sense of well-being he will not perform as effectively, and an optimum level of productivity will not be achieved. Health factors influenced by the indoor environment are (Clements-Croome and Kaluarachchi, 2001): (1) respiratory problems (dryness, hoarseness, dry/sore throat, changes in voice, wheezing); (2) skin problems (soreness, itching, dry skin, rashes); (3) nervous problems (headaches, nausea, drowsiness, tiredness, lethargy, reduced mental capacity, dizziness, forgetfulness, fatigue); (4) nasal-related problems (itchy or teary eyes, runny nose, asthma-like symptoms among non-asthmatics); and (5) odor complaints (changes in odor, unpleasant odors or tastes).

Motivation scale includes two items relating to worker's willing and enthusiasm to perform task. They were assessed on a 7-point scale ranging from 1 (very low) to 7 (very high). Well-being was assessed by 18-item questions covering comfort and health factors influenced by the indoor environment on a 5-point Likert-type scale ranging from 0 (not at all) to 4 (extremely).

2.2.4.4. National aeronautics and space administration-task load index (NASA-TLX). NASA-TLX is found to be the most valid measure of subjective workload, to have the highest user acceptance, and to have the smallest between-subjects variability. NASA-TLX is a multidimensional, self-reported assessment technique that provides an estimation of the overall workload associated with task performance and mental effort (Hart and Staveland, 1988). In TLX, workload is defined as the "cost incurred by human operators to achieve a specific level of performance." The overall workload score (OW) is a weighted average of ratings on six underlying psychological factors, including physical demand (PD), mental demand (MD), temporal demand (TD), own performance (OP), effort (EF), and frustration (FR) level. Three dimensions relate to the demands imposed on the participant (PD, MD, and TD) and three to the interaction of a participant with the task (EF, FR, and OP). NASA-TLX involves a two-part evaluation procedure. The first requirement is to obtain numerical ratings for each scale that reflect the magnitude of that factor in a given task on a 7-point bipolar scale ranging from 1 (low) to 7 (high). Second, participants perform 15 pair-wise comparisons of six workload scales. The number of times each scale is rated as contributing more to the workload of a specific task is used as the weight for that scale. Finally the overall workload score can be computed by multiplying each rating by the weight given to that factor. In this research, NASA-TLX was computerized and the six subscales of workload for a specific neurobehavioral test were evaluated immediately after the test was finished.

2.3. Experimental procedure

The effect of three indoor air temperatures (17 °C, 21 °C, and 28 °C) on productivity was studied. The indoor air velocity was kept under 0.1 m/s, and the relative humidity of air was not dependently controlled. Within-subject design was applied for this experiment and balanced Latin-square design was utilized to control the carryover effects (Zhu, 2000).

The experiment was performed in three days, each day for 8.5 h from morning to afternoon. Twenty-one participants were separated into 3 groups with 7 participants (5 males and 2 females, respectively) in a group, each group being exposed to the three temperature conditions in one day. A standardized three by three balanced Latin-square design was shown in Table 1, in which factor T was the experimental variable ($T_1 - 17$ °C, $T_2 -21$ °C, $T_3 - 28$ °C), factor A referred to the three participant groups, and factor B referred to the three successive time periods of each group. The schedules of the whole day and each temperature condition are shown in Fig. 2. There were two pauses among the three temperature conditions: from 11:00 to 12:30 was lunch time, participants being supplied with the same Chinese foods; and from 14:30 to 15:30 was the second interval time, during which participants went out of the office for a break and they could consume non-carbonated water and biscuits which were freely available at the waiting room. Each temperature condition lasted for a total of 120 min. First, participants entered the office reading book or playing games for 40 min to adapt to the indoor environment. During this period, physical parameters were measured. Following the exposure, participants spent about 60 min on performing the computerized neurobehavioral tests and assessing workload. After completing the neurobehavioral tests, participants were instructed to assess their general perceptions of the environment, emotions, well-being, and motivation to work by filling in questionnaires for 10 min. Then the physiological parameters of one of the seven participants were measured for 10 min. Participants were told before the experiment that they could not leave the room until the 120 min session had reached.

A week before starting the experiment, participants practiced the neurobehavioral test battery for 1 h. They were also instructed on how to fill out the questionnaires.

Table 1
Balanced Latin-square design of this experiment.

	B_1	B_2	B_3
A_1	T_1	T_2	T_3
A_2	T_2	T_3	T_1
A_3	T_3	T_1	T_2

2.4. Statistical analysis

The SPSS 13.0 (SPSS Inc., Chicago, IL, USA) program was employed to make the statistical analysis. The data were first tested for normality using Shapiro–Wilk's W test; the significance level

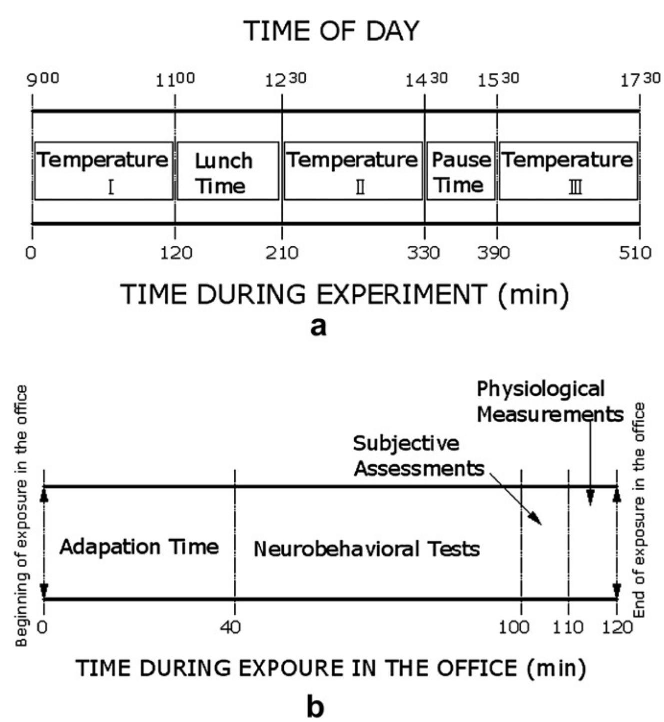

Fig. 2. Schedule of the experiment: (a) schedule of the whole day and (b) schedule of each exposure.

Table 2
Mean values and STD of physical parameters inside the office.

Parameter	28	21	17
Air temperature (°C)	28.2 ± 0.5	21.1 ± 0.6	18.0 ± 0.5
Relative humidity (%)	62.6 ± 7.9	71.3 ± 4.3	63.2 ± 3.9
Air velocity (m/s)	0.1 ± 0.03	0.08 ± 0.02	0.1 ± 0.03
Mean radiant temperature (°C)	28.1 ± 0.4	21.0 ± 0.5	18.1 ± 0.5
Illuminant (lx)	560.2 ± 56.3	561.4 ± 54.7	562.1 ± 54.0

was set to be 0.05 ($P < 0.05$). Normally distributed data were subjected to analysis of variance in a repeated measures design with each participant as her own control, thus excluding any differences in experience, training, intellectual skills, etc., which can influence performance greatly. Huynh–Feldt statistics were used to adjust the violation of sphericity. Huynh–Feldt's *P*-values were based on corrected degrees of freedom, though the original degrees of freedom were reported. Whenever necessary, post hoc comparisons (Turkey HSD test) were then performed. Not normally distributed data were analyzed using Friedman's analysis of variance or Wilcoxon Matched Pairs test.

3. Results

3.1. Results of thermal condition

The measured physical parameters describing the indoor climate of the office are shown in Table 2. They did not deviate from the intended level, and also there were no large differences in the relative humidity among the three conditions. The relationship between thermal sensation votes and air temperature is shown in Fig. 3. The relationship between thermal comfort votes and air temperature is shown Fig. 4. The size of the plot in Figs. 3 and 4 represents the number of replies. It can be seen that participants attained thermal neutrality and comfort at 21 °C; they felt slightly cool at 17 °C and slightly warm at 28 °C and most participants felt slight discomfort at these two conditions.

3.2. Results of emotion

The effect of air temperature on participants' emotion is illustrated in Table 3. The reliability (Cronbach's α) for the POMS total mood disturbance and subscales (ranging from 0.65 to 0.92) suggests that

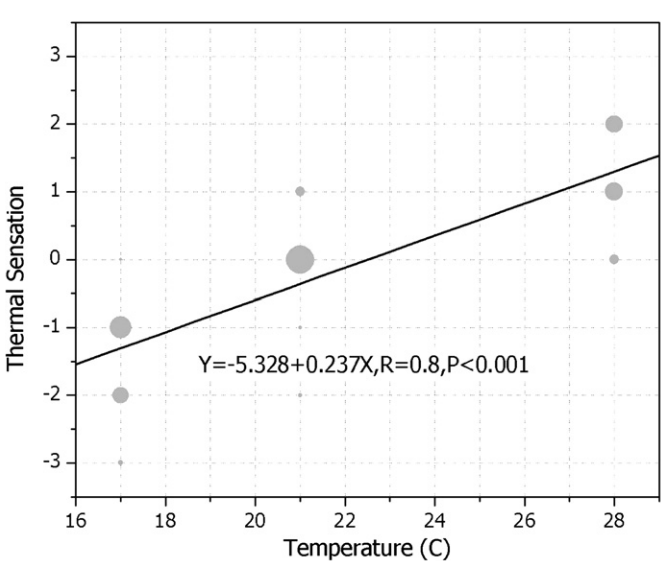

Fig. 3. Change in thermal sensation votes with air temperature.

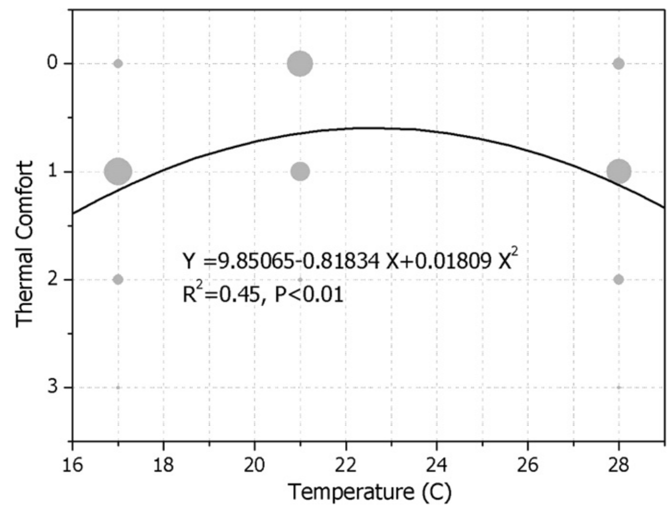

Fig. 4. Change in thermal comfort votes with air temperature.

the POMS is a reliable scale being used to investigate the effect of thermal environment on occupant's emotion. It should be noted that the higher score of negative moods, such as tension, depression, anger, fatigue, and confusion, indicates higher negative emotion, while the higher score of vigor indicates higher positive emotion. It can be seen from Table 3 that participants' tension and anger emotion and total mood disturbance were significantly affected by air temperature (Repeated-measure ANOVA, $P < 0.05$), they experiencing more negative moods at 28 °C and less negative moods at 21 °C (Post hoc test, $P < 0.05$). No significant emotional difference was observed between 17 °C and 21 °C, or between 17 °C and 28 °C.

3.3. Results of well-being and motivation

The effect of air temperature on occupants' well-being and motivation is shown in Fig. 5. It was found that occupants' perception of well-being and their motivation to work were also significantly affected by air temperature (Friedman ANOVA, $P < 0.05$). They perceived better well-being at cool condition and neutral condition than at warm (Wilcoxon Matched Pairs test, $P < 0.01$). As to motivation, they had significantly higher motivation to do work at neutral condition than at warm condition (Wilcoxon Matched Pairs test, $P < 0.05$). No significance difference in well-being or motivation was found between the neutral condition and the cool condition.

3.4. Results of workload and performance of neurobehavioral tests

The overall workload and the six subscales imposed by the neurobehavioral tests under different temperature conditions are

Table 3
The effects of air temperature on subjective emotional ratings.

	Internal consistency			Mean (SD)			P
Temperature (°C)	17	21	28	17	21	28	
Total mood disturbance (TMD)	0.87	0.83	0.88	26.8(5.1)	24.8(4.8)	32.6(5.1)	0.05*
Tension	0.80	0.75	0.70	7.8(1.0)	6.5 (0.7)	8.6(0.9)	0.05*
Depression	0.91	0.83	0.85	11.3 (1.8)	10.1(1.7)	12.1(1.7)	0.14
Anger	0.87	0.81	0.81	7.5(1.2)	6.3(0.9)	8.7(1.4)	0.04*
Vigor	0.85	0.90	0.83	15.5(1.2)	14.7(1.3)	14.5(1.3)	0.54
Fatigue	0.89	0.87	0.92	7.6(0.9)	8.6(1.1)	9.5(1.1)	0.06
Confusion	0.68	0.65	0.67	9.0(0.7)	8.9(0.7)	9.3(0.7)	0.79

*$P < 0.05$.

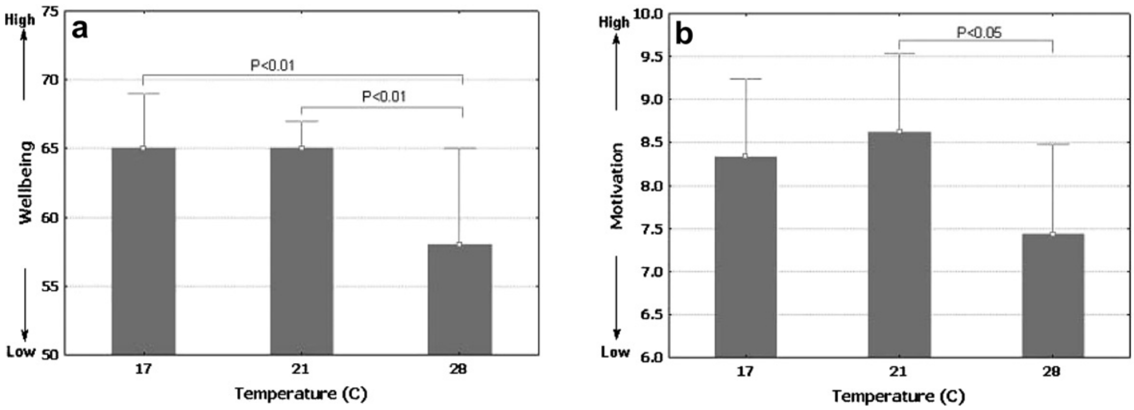

Fig. 5. Change in (a) perception of well-being and (b) motivation to work with air temperature.

shown in Fig. 6. The air temperature had significant effects on the perceived overall workload as well as the subscales (except the physical demand subscale) (Friedman ANOVA, $P < 0.05$). It can be seen that participants perceived that workloads were significantly higher at 17 °C and 28 °C than that at 21 °C. The results of the six subscales indicate that the neurobehavioral tests were characterized by significantly higher mental demand than physical demand (Repeated-measure ANOVA, $P < 0.05$), and well represent the characteristics of current office works. Significant effect of air temperature on effort was observed (Repeated-measure ANOVA, $P < 0.05$). Post hoc test shows that participants had to perform tests with significantly more effort at 17 °C than at 21 °C.

Fig. 7 shows the relationship between indoor air temperature and the performance of neurobehavioral tests based on regression analysis. The real lines indicate the variation of accuracy and speed with air temperature, and the broken lines illustrate the 95% confidence interval. It can be seen from Fig. 7 the trend that the accuracy and speed of neurobehavioral test decreased in the moderately uncomfortable environment. However, no significant effect of air temperature can be observed on the performance of most neurobehavioral tests.

The correlations between workload and performance of neurobehavioral tests are shown in Table 4. The correlation factors were analyzed with Spearman coefficients. It can be seen that participants had to exert more effort to perform tasks when the mental demand and time demand were higher. However, negative correlation was found between exerted effort and the accuracy and speed of neurobehavioral tests, indicating that although participants had exert more effort to do task no improvement on performance could be achieved. Moreover, both accuracy and speed of neurobehavioral tests decreased with the increase of overall workload, that is, participants having poorer performance when the workload was higher.

Table 5 illustrates correlations of overall workload (OW), emotion (TMD), well-being (WB), motivation (MT), and the performance (accuracy and speed) of neurobehavioral tests. The correlation factors were analyzed with Spearman coefficients. There is a positive correlation between motivation and well-being, both of which decreased with increase of total mood disturbance score and overall workload. But no significant correlation can be found between the performance of neurobehavioral tests and emotion, well-being, or motivation.

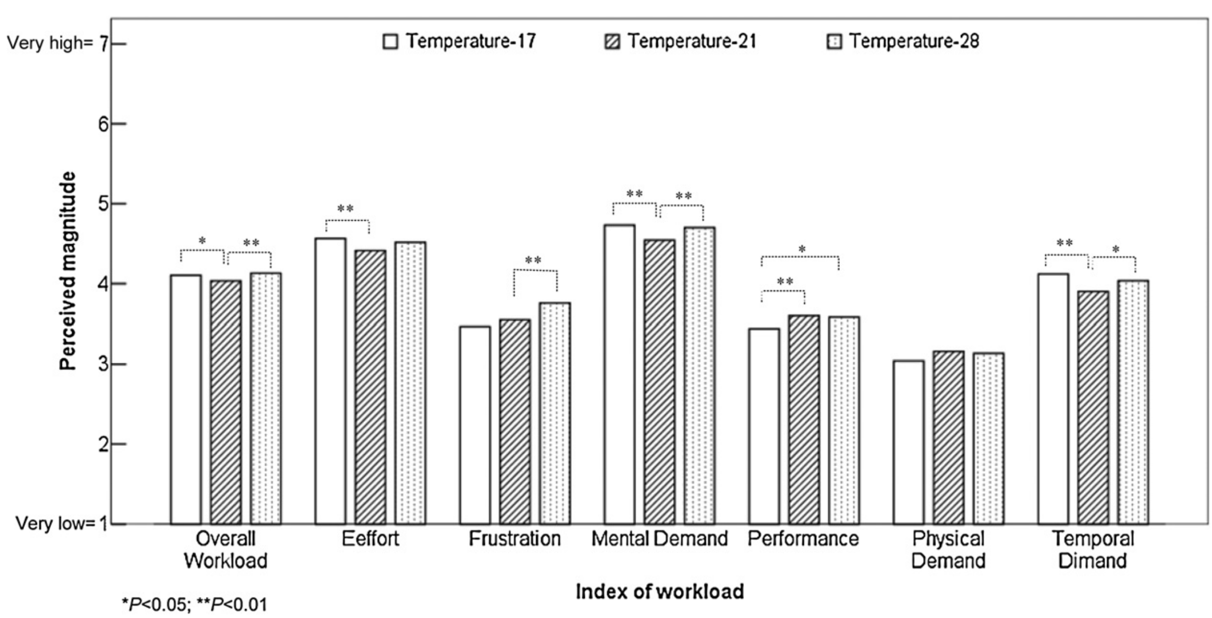

Fig. 6. Change in overall workload and the six subscales with air temperature.

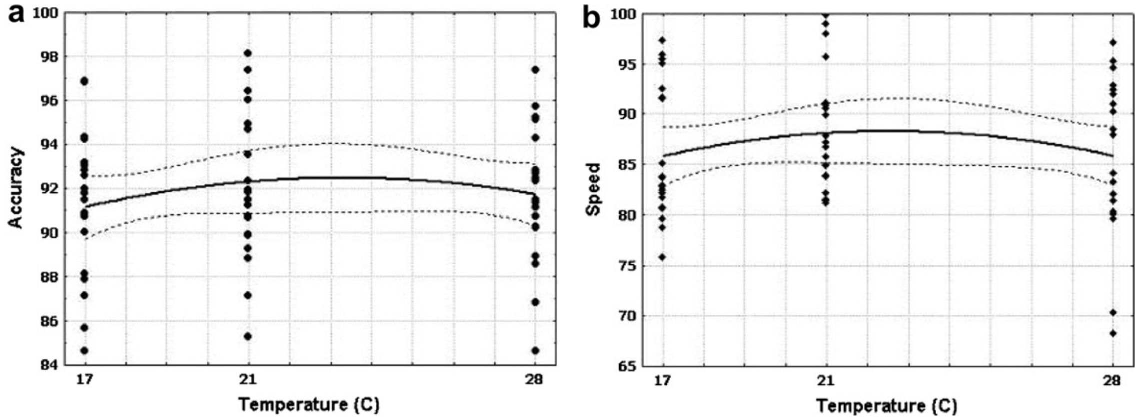

Fig. 7. Change in performance of neurobehavioral tests: (a) accuracy; (b) speed with air temperature.

3.5. Results of HRV and EEG

In this study the physiological parameters of 3 participants were measured. Fig. 8 shows the variation of LF/HF with air temperature. It can be seen that the LF/HF increased with air temperature although no significant statistical temperature effects was found; great increase in the LF/HF ratio was found at the 28 °C compared with another two conditions. The global relative power of the four EEG bands is shown in Fig. 9. The power of δ-band EEG was significantly affected by air temperature (Repeated-measure ANOVA, $P < 0.02$). The δ-band EEG decreased at the 17 or 28 °C compared with the neutral condition (Post hoc test, $P < 0.05$). No significant changes of other three EEG bands were found but it can be seen from Fig. 9 that both α-band and β-band EEG increased at the 17 and 28 °C.

4. Discussion

This study suggests that participants maintained their performance by exerting more effort when the workload demand increased in thermal discomfort environment. Haneda et al. (2009) found similar results when examining the effects of thermal discomfort on the performance of office work. Just as it is defined, effort, consciously protecting the level of task performance by ‘trying hard’, can counteract an impaired operator state as well as enable dealing with increased task demands (Hockey, 1986). On the other hand, studies have validated the existence of a ‘cognitive reserve’, whereby participants have at their disposal a certain amount of neural resources that could be allocated to the performance of tasks and activities. Performance of these tasks and activities would deteriorate when the amount of resources was insufficient to deal with both the task demands and thermal stress, such that participants would be able to maintain their performance level until the resources were overloaded (Hocking et al., 2001). Moreover, participants would like to exert more effort to maintain performance if needed when they were supplied with extra bonus for better performance. The investment of effort has the advantage that task performance remains at a certain target level, but there are costs for this achievement. Short-lasting effort investment is probably without health consequences and is one of the advantages of human flexibility to deal with in demands. However, prolonged, continuous effort compensation can be a threat to good health, as it has been suggested that repetitive activation of the cardiovascular defense response may lead to hypertension (Johnson and Anderson, 1990).

The cost of effort investment can be partly illustrated by participants’ motivation to work: they had lower motivation to work when they had to exert more effort to perform a task. Motivation plays an important role in worker productivity. Heerwagen (1998) showed that the relationship between buildings and worker performance was related to both motivation and ability. An individual has to want to do the task and then has to be capable of doing it. In addition to effort investment, well-being is also related to motivation to work. As to the health condition, participants reported significantly more SBS symptoms at the warm condition. Fang et al. (2004) also found the perception of air freshness and acceptability improved greatly as temperature decreased and the intensity of fatigue, headache and difficulty in thinking clearly decreased at lower levels of air temperature. The conditioning of the mucous membrane in the upper respiratory tract induced by the temperature and water vapor difference between the inspired air and the surface of the nasal passage potentially alleviated the perceptions of poor air quality in the neutral and cool environment (Berglund and Cain, 1989; Fang et al., 2004). Due to the above reasons, high air temperature significantly reduced participants’ motivation to do their work. In fact, the confidence that the fight for a healthy work environment and healthy workers is a prerequisite for innovation and productivity in a knowledge-based economy, is gaining more and more ground in companies (Hermans and Peteghem, 2006).

Table 4
Correlations among workload and performance of neurobehavioral tests.

	PD	MD	TD	OP	EF	FR	Accuracy	Speed
OW	0.26**	0.64**	0.52**	−0.52**	0.76**	0.71**	−0.19**	−0.14**
PD		0.04	0.10**	−0.10**	0.05	0.25**	0.02	−0.02
MD			0.27**	−0.14**	0.47**	0.36**	−0.16**	−0.09**
TD				−0.06	0.30**	0.26**	0.02	0.02
OP					0.21**	0.37**	−0.28**	−0.11**
EF						0.51**	−0.08*	−0.12**
FR							−0.10**	−0.11**
Accuracy								0.01

$*P < 0.05$; $**P < 0.01$.

Table 5
Correlations among emotion, well-being, motivation, and performance.

	TMD	WB	MT	Accuracy	Speed
OW	0.24**	−0.25**	−0.12**	−0.19**	−0.14**
TMD		−0.48**	−0.27**	−0.02	0.01
WB			0.64**	0.03	0.01
MT				0.06	−0.10
Accuracy					0.01

*$P < 0.05$; **$P < 0.01$.

The role of emotion has been largely neglected in productivity research. Frijda (1996) suggested that the ultimate function of emotions is to potentiate or stimulate behavioral responses that, in turn, influence the person–environment relation in the service of some adaptive goal. Damasio (1994) also claimed that emotion can provide an early warning to the cognitive system as to whether things are going well or badly and indicate which things need attention. In particular, intense and negative emotions may reduce performance efficiency in several ways: (a) they may disrupt the state regulation, which makes it less optimal for task performance because of over-reactivity; (b) they may be so distracting that they directly interfere with the processing of the task information; or (c) they may cause psychosomatic complaints that also demand attention. The correlations between emotion and motivation show that negative emotion reduced participants' motivation to do work. Participants experienced more negative moods at the warm condition, so they even did not want to exert as much effort as the slightly cool condition when they felt that the environment was unfavorable and it was hard to maintain their performance.

However, no significant correlations can be found between performance of neurobehavioral tests and emotion, or well-being, or motivation. There are several explanations for this dissociation; the time lag between taking performance measures and subjective rating, or the dynamic interaction between people and their overt performance. There is a continuous and dynamic interaction between people and their surroundings that produces physiological and psychological strain on the person. The humans' body is not a passive system that responds to an environmental input in a way that is monotonically related to the level of the physical stimulus (Parsons, 2000). Instead, acting as an adaptive agent, humans regulate the effect of indoor environment imposed on their productivity. They keep on appraising their environment consciously or unconsciously and choose coping strategies and self-regulative processes that are believed to be appropriate. Productivity is the final result of those

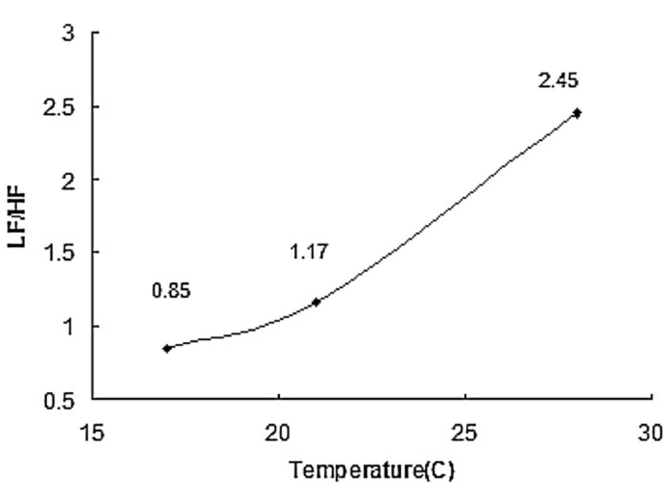

Fig. 8. Ratio of low frequency to high frequency (LF/HF) under different air temperatures.

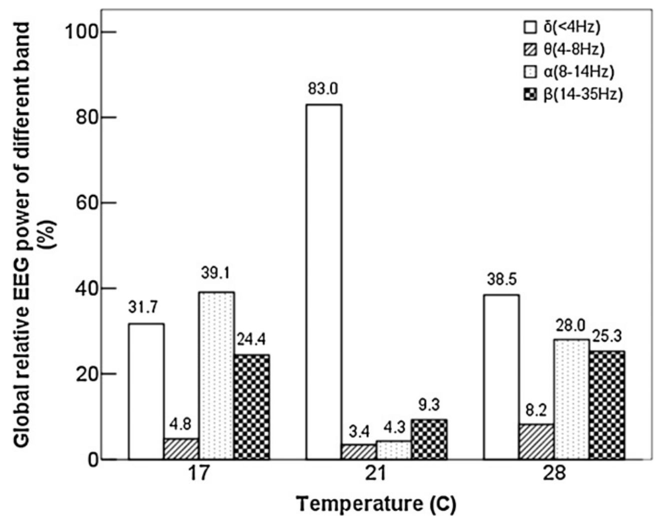

Fig. 9. Effect of air temperature on EEG power of different bands.

behaviorally manifestations of human psychological, physiological, and neural functioning changes. Due to the flexibility of human beings, the effects of indoor environment on productivity may not be illustrated overtly on neurobehavioral performance during the experimental period. In this study, participants succeeded to maintain their performance by exerting more effort in the moderately uncomfortable environment when they were encouraged by extra bonus. On the other hand, they also realized that they could leave the environment after the short experiment, which helped them to overcome the effects of adverse thermal environment during the experimental period. This is probably one of the main limitations of laboratory study on productivity. However, the lower motivation to do work, higher perceived workload, and more negative emotions might indicate that productivity will be reduced in an uncomfortable environment in real life. Moreover, when subjective assessments are taken together with performance measures, whether dissociating or not, reveals more about task performance than performance measures taken in isolation.

The HRV index has been shown to be closely related to thermal comfort sensations; the LF/HF was higher when the participants stayed in the unpleasant thermal environment (Yao et al., 2009). In this study, when stayed in the warm environment, participants' LF/HF was twice as much as that when they were neutral or slightly cool, which may suggest that they felt discomfort at the warm environment. However, it is not clear why no increase of LF/HF value was found in the slightly cool condition. Just like Yao et al.'s (2009) research, the present study also found an increase of δ-band EEG and decrease of β-band EEG in the neutral environment. The δ-band EEG is usually associated with slow-wave sleep. This result may indicate that participants were tired after 2 h work and they could have a good relax in the comfortable but not in the uncomfortable environment. One limitation of this study is that only limited samples (3 participants) of physiological measurements were made after the tasks; it would be better if they were made along with tasks at the same time. However, the results still support useful evidence together subjective assessments that thermal discomfort has negative influence on occupants' productivity.

5. Conclusions

In the field laboratory experiment subjective rating scales and physiological measurements were made to evaluate the effects of air temperature on productivity. It can be concluded that:

- Participants had lower motivation to do work and their δ-band EEG decreased in the moderately uncomfortable environment.
- Warm discomfort increased the LF/HF value and negatively affected participants' well-being.
- The workload imposed by neurobehavioral tests increased in the moderately uncomfortable environment and participants had to exert more effort to maintain their performance with the increase of workload.
- Thermal discomfort caused by high or low air temperature had negative influence on office workers' productivity and the subjective rating scales were important supplements of neurobehavioral performance measures when evaluating the effects of IEQ on productivity.

In the future experiments, more participants will be involved, longer exposure session (for example, at least 4 h) should be investigated, and the extra bonus may not be supplied anymore to make the experiment environment more like the actual work environment. An effort should be also made to integrate the two indices of accuracy and speed into one index, as productivity concerns not only the quantity of work, but also the quality of work.

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