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Influence of indoor air temperature on human thermal comfort, motivation and performance

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ABSTRACT

In this study, subjective experiments were conducted to evaluate the effects of air temperature on thermal comfort, motivation, performance and their relationship. Steady-state environments at five different temperatures (22 °C, 24 °C, 26 °C, 29 °C, 32 °C) were created in a climate chamber. Thirty six subjects (eighteen males and eighteen females) were recruited and they were divided into Group A and Group B. Group A was exposed to all five temperature conditions while Group B was only exposed to 26 °C. Thermal sensation, thermal comfort, motivation and workload were measured with questionnaires. The task was memory typing and the number of correct letters was used to evaluate performance.

It has been proven in this study that the learning effect was greatly affected by temperature. Under warm or cold discomfort environment or when the temperature was frequently changing, the learning rate was slowed down. Motivation improved when people were more comfortable and performance also increased because of higher motivation. So the change in performance was not only contributed by objective environment factors (air temperature in this study) but also by subjective factors like motivation. Stepwise regression showed that the change of human performance could be better explained by the change of motivation than the change of air temperature.

Significance test shows that the optimum temperature range for performance in this study was between 22 °C (slightly cold) and 26 °C (a little higher than neutral). Warm discomfort environment had negative effect on both motivation and performance.

1. Introduction

Studies [1–3] have identified that human performance bears a close relationship to the indoor environment quality (IEQ). The IEQ covers several factors, including thermal environment, indoor air quality, lighting, and acoustic, etc. Air temperature is the commonly used indicator of thermal environment in IEQ and performance research. In the present study, the relationship between performance and air temperature was reviewed.

Numerous field and laboratory investigations have been conducted to study the relationship between air temperature and human performance. Several studies have proved that air temperature influences performance indirectly through its impact on prevalence of SBS symptoms or satisfaction with air quality [4,5]. Meanwhile air temperature also directly affects human performance. Berglund et al. [6] and Niemela et al. [7] reported a decrement in performance of call center workers when the temperature was above 25 °C. Federspiel et al. [8] also surveyed call center workers and found no significant effect of temperature on performance in the comfort zone. Due to the complexity of performance measurement in field study, most researchers conducted their experiments in laboratory. Johansson [9] designed three environment conditions with effective temperatures of 24 °C, 27 °C and 30 °C in the chamber. The results revealed that for most forms of mental work the optimum temperature was 24 °C but for perceptual tasks a conversed U-curve was observed with the best performance at 27 °C. Pepler and Warner [10] investigated the relationship between time to complete a task and temperature and found it took the longest time to finish the task at 26.7 °C with the lowest error rate. Lan et al. [11–14] applied neurobehavioral tasks to measure human performance under three temperature levels (17 °C, 21 °C and 28 °C). Performance decreased when thermal environment deviated from neutral condition and participants experienced more negative emotions and had to exert more effort to maintain their

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performance under moderately adverse environmental conditions. It is recommended that the PMV (Predicted Mean Vote) range for general comfort is from −0.5 to 0.5 in ASHRAE standard 55-2010 [15]. Lan et al. [14] suggest that the range for comfort zone in workplaces should be between −0.5 and 0 to avoid performance loss. Cui et al. [16] measured human performance under dynamic environments with airflow from neutral to slightly warm and reported no significant performance change in all three simulated tasks (pattern matching, addition and memory typing).

Through all these years' research, it is generally agreed that there should be an optimum temperature or more precisely, an optimum temperature range for performance. However, great divergence came up when they tried to define the range. Lan et al. [14] suggested the optimal range should be from slightly cold (PMV = −0.5) to neutral (PMV = 0). However, Witterseh [17] found that there was no significant effect of temperature on performance from neutral temperature (22 °C) to slightly warm discomfort temperature (25 °C). Lorsch [18] stated that only when temperature was above a critical zone (between 32.2 °C and 35 °C) mental performance accuracy declined. Although the results were different, the comfort zone should be all or partly contained in this range. Yet several studies provided evidence of better performance outside the comfort zone due to arousal effect of the environment. Razmjou [19] proved that the deficit of mental performance in the heat could be offset by an increase in arousal, particularly when task demand was low. The final conclusion of each research was largely dependent on the experiment design, the data analyses method and the nature of the performed tasks which Wyon [20] has found.

Some researchers tried to establish a quantitative relationship between temperature and performance. Seppänen et al. [21] proposed that in the temperature range of 25–32 °C performance decreased 2% with 1 °C increase and no such change was found in temperature range of 21–25 °C, which was confirmed by Tanabe et al. [22].

Previous researches mainly focus on the influence of environment on performance yet little information is available on the influence of human mental state. In other words, only the influence of objective environment factors was measured in most previous studies. For performance, the working motivation is an important subjective factor which has already been introduced by Lan et al. [13]. Lorsch [18] revealed that motivated people could maintain high performance for a short time under adverse (hot or cold) environments. However, it was still unclear how performance was affected by motivation. Besides, the learning effect is also very important for performance evaluation and has not been addressed clearly in former researches.

Thus the main purpose of this paper is to clarify the influence level of objective factor (temperature) and subjective factor (motivation) on human performance. Series of experiment were conducted in a climate chamber. The task used was memory typing, which required relatively high mental demand similar to office tasks. Two groups of subjects exposed to different conditions were designed to investigate how learning effect would be influenced by temperature. Methods to remove learning effect were also discussed.

2. Methodologies

The experiment was carried out in an artificial climate chamber ($L \times W \times H = 5 \times 4 \times 3$ m), in which participants sat at four workstations, each consisting of a table, a chair and a computer. The chamber was controlled by an air handling unit, and the control accuracy for air temperature and relative humidity was ±0.5 °C and ±5% respectively. The air was supplied through perforated ceiling and returned from the floor. The background air velocity was controlled below 0.1 m/s, which was imperceptible. The wall surface is made of PVC material and foamed plastics are filled in so thermal conductivity of the wall is low.

2.1. Participants

A total of 36 Chinese adults (18 males and 18 females) were recruited to participate in the experiment. The participants were all university students (average age 22.3). Before entering the chamber, subjects were required to wear uniform clothes, containing long-sleeved shirt, long thin trousers, underwear, socks and slippers with an estimated clothing insulation value of 0.7clo (1clo = 0.155 m^2 K/W) including the insulation of the chair. All subjects were healthy and they were required to have a good rest before the experiment. The participants were paid a salary for participation in the experiment at a fixed rate per hour with no additional bonus. All subjects successfully completed experimental sessions.

2.2. Experimental conditions and procedure

A total of five conditions were designed and they were all steady-state conditions (22 °C, 24 °C, 26 °C, 29 °C, 32 °C). The subjects were divided into Group A and Group B. Group A contained 20 subjects and Group B contained 16 subjects. The number of male and female was equal in both groups. Subjects in Group A participated in all five conditions and for comparison Group B was exposed to only one condition (26 °C). The purpose was to find out whether learning effect would be affected by temperature.

Within-subject design was applied for Group A. Therefore, individual differences could be offset more efficiently. Group A was divided into five smaller groups with 4 subjects (2 males and 2 females) in a subgroup. A five by five balanced Latin-square design was utilized to control the sequence effect as shown in Table 1.

Group B was also divided into 4 subgroups and each with 4 subjects (2 males and 2 females) and each subject had to participate for five times under the same temperature condition (26 °C) .The subgroup sequence of first experiment was randomly arranged and this sequence remained the same in the following four experiments. In both Group A and Group B, the experiment time and the interval between two experiments for each subgroup were the same, in order to reduce the influencing factors as much as possible. If a subgroup was arranged for the first experiment from 9:00 to 11:30 in the morning, they would always had experiment in the same time period in the following four experiments. The exposure interval for Group B was one day and two day for Group A because one day interval was not enough for all five subgroups to take experiments.

Pre-experiment training was performed. The task was given to each subject a week before the experiment started. And to ensure the training was effective, a relatively high standard was set and the subjects must surpass this line and send us the data. When the

Table 1
Experiment design using Latin-square method for Group A.

		Experiment sequence				
		1	2	3	4	5
Subgroup	1	32 °C	29 °C	24 °C	26 °C	22 °C
	2	26 °C	32 °C	22 °C	24 °C	29 °C
	3	22 °C	24 °C	32 °C	29 °C	26 °C
	4	24 °C	26 °C	29 °C	22 °C	32 °C
	5	29 °C	22 °C	26 °C	32 °C	24 °C