Overall effects of temperature steps in hot summer on students' subjective perception, physiological response and learning performance

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Abstract: University students are very likely to experience temperature steps before class in hot summer. This study aims to investigate the overall effects of step changes on students' subjective perception, physiological response and learning performance, so as to explore an optimal thermal condition for classrooms in hot summer. Four typical temperature step conditions (S6: 34℃-28℃, S8: 34℃-26℃, S10: 34℃-24℃, S12: 34℃-22℃) were developed to conduct experiments on sixteen participants. It has been found that after temperature steps, no more than 62.5% of students consistently found thermally acceptable at 22℃; students felt the most acceptable and comfortable at 26℃; the effect of thermal environment on workload was not significant in most cases, especially for memory-related tasks; students' negative mood was less at 26°C than at 28°C and 22°C. When the temperature step was less than S12, blood pressure and blood oxygen saturation were insensitive to temperature steps; core temperature continued to rise during the first 5 minutes and then decreased significantly when the temperature step exceeded S8. No significant difference in learning performance was found among the four conditions; the differences in relative performance between thermal conditions were less than 2%, and are not likely to have practical meaning in building management practice. Overall, the optimal thermal condition is 26℃, and it is recommended to set the indoor temperature between 24-28℃.

Keywords: Temperature step; Thermal perception; Physiological response; Learning performance; Classroom

Received 16 October 2020, Revised 10 May 2021, Accepted 19 May 2021, Available online 21

May 2021.

Highlights

No more than 62.5% of students consistently found thermally acceptable at 22°C.

Students' negative mood was less at 26°C than at 28°C and 22°C.

Core temperature decreased significantly when the temperature step exceeded 8°C.

No significant difference in learning performance after different temperature steps.

The optimal thermal condition is 26°C after temperature steps.

List of abbreviations

TSV	Thermal sensation vote
TCV	Thermal comfort vote
TAV	Thermal acceptance vote
TPV	Thermal preference vote
NASA-TLX	National aeronautics and space administration task load index
POMS	Profile of mood states
BP	Blood pressure
DBP	Diastolic blood pressure
SBP	Systolic blood pressure
HR	Heart rate
SPO2	Blood oxygen saturation
T_{cr}	Core temperature
a1	Simple Attention Blinking
a2	Test of Variables of Attention
m1	Digital Span
m2	Serial Probe Recognition
p1	Stroop

p2	Visual Search
t1	Sequence of Baddeley's 3-minute Grammatical Reasoning Test
t2	Number Bisection

1. Introduction

In the past few decades, global warming and the urban heat island effects have jointly aggravated the frequency, intensity, and duration of extreme hot weather events in cities and urban areas [1-3]. In addition, China's rate of temperature increase has been significantly higher than the global average over the same period. The average annual surface temperature of China showed a remarkable upward trend from 1901 to 2018 [4]. The thermal environment affects people's physical and psychological states continuously and dynamically, leading to changes in health, well-being and performance [5-7]. In order to ensure the thermal comfort and learning performance of students, air conditioners have been commonly installed in classrooms of universities in China. However, due to the discontinuity of curriculum arrangements and the dispersion of classroom locations, university students always have to walk from the hot outdoors to indoor classrooms. Moreover, class breaks in open corridors, typical in hot regions, will also make students experience temperature steps.

In an attempt to control thermoregulation burden, a number of studies have investigated the subjective perception and physiological response of subjects to temperature steps [8-12]. Gagge et al. [8] conducted the first experiment of temperature step in a climate chamber with three subjects and observed the cooling overshoot phenomenon. Subjects' thermal perception and physiological parameters were found to be more sensitive to temperature down steps [10, 11, 13, 14]. In addition, both thermal sensation overshoot and significant physiological variations failed to occur when temperature step was less than 5℃ [15]. After the temperature steps, human body's thermoregulation system would actively adjust according to the thermal conditions to re-establish a new thermal balance. The resulting excessive changes in relevant physiological parameters (such as increased systolic blood pressure) could damage health [16]. The time to achieve a stable state mainly depends on the direction and magnitude of temperature steps [11, 13, 17, 18], the age of participants [16], and the body parts measured [10, 13]. Moreover, Zhai et al. [19] stated that the setting of indoor temperature should consider the changes of metabolic rate, and people preferred a lower room temperature which provided adequate cooling after summer commutes. A limited amount of studies have investigated the cognitive performance of subjects after experiencing temperature changes [20]. Direct load control of air-conditioners is a common strategy for managing peak power demand of university lecture halls, and Zhang and de Dear [21] studied the learning performance of students under temperature cycle triggered by direct load control. As heat exposure time increased, subjects' reasoning and planning performance showed a downward trend. Muller et al. [22] conducted an experiment in which participants experienced two hours of cold exposure (10℃) and two hours of rewarming (25℃). A decline in cognitive function was found during the rewarming phase after acute cold exposure compared to the baseline condition. The temperature changes have an impact on occupants' thermal perception and physiological state, which may also affect their cognitive performance. However, the effect of temperature down steps on students' learning performance in hot summer was not explored. Furthermore, as subject's thermal perception and physiological indicators were measured at rest, previous research may not be sufficient to fully understand the effects of typical summer temperature steps on students' subjective perception and physiological responses during the lecture time.

In terms of stable thermal environment, a plethora of researches have been devoted to exploring the relationship between thermal conditions and cognitive performance. Some researchers reported that the relationship follows an inverted U-shaped curve [23-28]. Occupants show the best performance at an optimal temperature, while perform relatively poorly at lower or higher temperatures. Seppanen et al. [23] observed that cognitive performance decreased by 2% with per ℃ increase of temperature when it was in the range of 25℃-32℃. Furthermore, Lan et al. [24] found that optimal cognitive performance was achieved when temperature was close to 22℃ or thermal sensation vote (TSV) was close to 0. Similarly, Geng et al. [25] carried out 7 sets of experiments in controlled office environment from 16℃ to 28℃ with a step of 2℃, and noticed that office environments made people feel "neutral" or "slightly cool" were conducive to productivity. Cui et al. [26] stated that the warm discomfort environment impaired work performance by affecting subjects' motivation. In addition to office environments, Wargocki et al. [27] reported a meta-analysis of published evidence on the relationship between children's learning performance and temperature in temperate climate, and the analysis showed that the optimal temperature is close to 22°C in the range of 20-30°C. Porras-Salazar et al. [28] confirmed the validity of findings from moderate climates to tropics, and results indicated that students' performance of schoolwork improved when classroom temperature was reduced from 30°C to 25°C. Instead, some researchers suggested that the effect of temperature on performance fits an extended U-shaped curve, and occupants could maintain a near-optimal level of performance under a broad range of thermal environment [29-32]. For example, Witterseh et al. [29] found no thermal effects on task performance when the temperature was set to 22-30℃. Fang et al. [30] suggested that performance of office work was not significantly affected by indoor air temperature when it was in the range of 20℃-26℃. Schiavon et al. [31] observed that the availability of personally controlled fan could mitigated the negative effect of the elevated temperature on thermal comfort, with no impairment in cognitive performance. In addition, through EEG analysis, Zhang et al. [32] verified that a higher temperature setpoint (25°C) will not jeopardize occupants' cognitive load and performance compared to the 22°C. However, these studies were carried out under the assumption that occupants performed lengthy sedentary activities in a fixed room, which cannot be used to determine the learning performance of students after temperature steps.

University is a crucial period for students to acquire key knowledge and skills to pursue a successful career and contribute to society after graduation [33], while classrooms are the main place for learning activities. The thermal environment of classrooms not only needs to ensure physical and mental health of students, but also to facilitate efficient learning. It seems that a low temperature setting may be conducive to cognitive performance, but an instant cold exposure could potentially threaten health conditions.

Considering the limitation that existing studies rarely discuss the students' learning performance in response to temperature steps, this study aims to investigate the overall effects of step changes on students' subjective perception, physiological response and learning performance, so as to explore an optimal thermal condition for classrooms in hot summer. The specific aims include: 1) investigating the subjective perception, in terms of thermal comfort, workload and mood of students after temperature steps; 2) investigating changes in students' physiological indicators (including blood pressure (BP), heart rate (HR), blood oxygen saturation (SPO2), and core temperature (T_{cr})) after temperature steps; 3) revealing the effect of temperature steps on learning performance; and 4) exploring an optimal thermal condition for classrooms after temperature steps.

To answer these research questions, four typical temperature step conditions in hot summer were developed to conduct the laboratory experiment on participants. Subjective perception of participants was recorded through questionnaires, and physiological indicators were measured using physiological instruments. Participants were invited to complete typical cognitive tasks to test their learning performance under the four thermal conditions.

2. Methodologies

2.1 Experimental setup

The experiment was carried out in Wuhan (29.58°N, 115.05°E), a typical city in central China, which is hailed as one of China's "four major stove cities". The mean maximum temperature in Wuhan in June and July 2018 was 31°C and 34°C, respectively [34]. In addition, the Chinese Indoor Air Quality Standard has recommended the indoor temperature to be between 22℃ and 28℃ in summer [35]. Therefore, four different conditions (S6: 34°C-28°C, S8: 34°C-26°C, S10: 34°C-24°C, S12: 34°C-22°C) were set up to simulate the situation of students entering the classroom from the outside in hot summer.

2.2 Experimental room

The experiment was conducted in three adjoining typical rooms in Huazhong University of Science and Technology, and the layout of experiment rooms can be seen in Fig. 1. Among them, Room1 was used for rest, Room2 was used to simulate the outdoor high temperature environment, and Room3 was used to simulate the indoor environment. To avoid the influence of external environment on indoor thermal conditions, thermal insulation films were attached to the windows. The interior wall thickness of the three rooms is 120mm. Since participants sat or walked in the middle of the room, the effect of the interior wall's surface temperature affected by the temperature of the next room on the participants may be weak. Each room was equipped with an air conditioner, and two heaters were placed in Room2. Based on the pilot experiment, two basins of water were placed in the corner of the rooms to adjust the relative humidity when the temperature was set to 22°C, 24°C and 34°C. The experimental conditions were set up one hour in advance before the participants entered the room. As shown in Fig. 1, the doors of the second and third rooms are side by side, and participants could immediately enter Room3 from Room2, to minimize the effect of temperature change in the corridor.

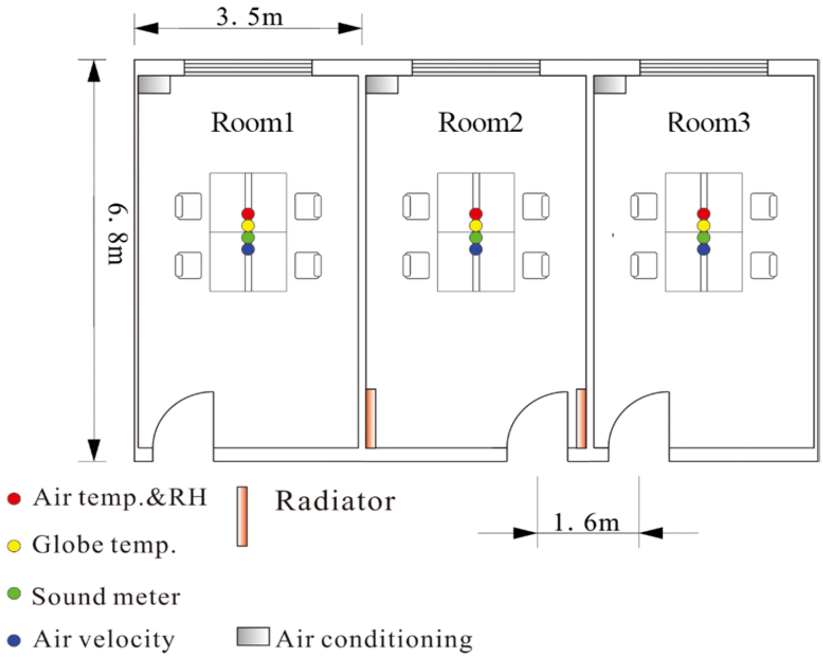


Fig. 1 Layout of the experimental rooms.

2.3 Participants

The data collection protocol was approved by the review board of School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology. Before the experiment, all participants were provided and signed an informed consent form that explains the confidentiality of data and their rights. Sixteen healthy university students participated in the experiment, and they have lived in Wuhan for more than two years. The exclusion criteria included sick in a week before the experiment, a history of health problems diagnosed like high blood pressure, neurological problems and regular medication, and color blindness or skin diseases that affect temperature perception. The number of participants was determined based on a power analysis using G*Power 3 [36, 37]. Similar studies suggested that the effect sizes of the tests we applied in the experiment were usually above 0.35 [24, 38]. When all participants were exposed to four thermal conditions with an effect size of 0.35 and a power level of 0.8, the required sample was around 13. In addition, previous studies with similar study design also indicated that experiments were conducted in a size of 3-30 subjects [39]. Participants included eight male and eight female students, and the demographic information of the subjects is shown in Table 1. Each subject was marked with a unique number, from one to sixteen. Participants numbered 1, 2, 5, 6, 9, 10, 13, 14 were female, and participants numbered 3, 4, 7, 8, 11, 12, 15, 16 were male. During the pre-experiment, the participants' reaction time and accuracy of learning performance tests were recorded. Their performance was similar, because the intraclass correlation coefficients was greater than 0.75 when the final learning performance of participants in the pre-experiment was used for consistency test.

Table 1

Demographic information of participants (mean value ± standard deviation).

Gender	Sample size	Age(y)	Height(m)	Weight(kg)	BMI(kg/m^2)
Male	8	23.6(0.9)	1.74(0.04)	66.13(5.11)	22.02(2.14)
Female	8	23.4(0.7)	1.63(0.05)	50.16(4.55)	18.99(1.23)
Total	16	23.5(0.8)	1.68(0.07)	58.14(9.33)	20.50(2.32)

Pre-experiments were conducted three days before the experiment, and experimental procedure and questionnaire items were explained minutely. Participants agreed that the cognitive test was an appropriate challenge for them. The format of learning performance tests was the same as that done by the participants in the formal experiment.They were asked to repeat the tests until the learning effect was almost removed [26], that is, when the consistency test result of the participants' last three test data showed good consistency of retest. Participants were instructed to dress according to their own comfort based on the outdoor high temperature environment (34°C) during the experiment, and the statistical result showed that the thermal insulation was 0.5±0.1, accounting for that of chairs.

2.4 Physical measurements

The environmental parameters of experimental rooms were continuously measured. As shown in Fig. 1, the measuring points were located at the center of the four participant positions, and the measuring height was 1.1m, which is the head level of seated occupants, according to ASHRAE Standard 55-2017 [40]. Instruments used to record the physical environment parameters are listed in Table 2, which is generally within the measurement accuracy range required by ISO 7726 standard [41]. Air temperature and relative humidity were recorded every 10s, and air velocity and globe temperature were measured every 1 minute. In addition, the sound pressure level had a frequency of every 300ms.

Table 2

Measurement instruments.

Type	Parameter	Range	Accuracy
AZ8829	Air temperature	-40~85°C	±0.6°C
	Relative humidity	0~100%	±3%
ST-732	Air velocity	0.00~40.00m/s	±0.03m/s
TM-188D	Globe temperature	0~59.0°C	±0.6°C
AWA6228+	Sound pressure level	20~140 dB(A)	±0.7dB(A)
Omron HEM-7124	BP	0~299 mmHg	±3mmHg
	HR	40~180/min	±5%

Omron MC342FL	T_{cr}	32~42℃	±0.1℃
Yuwell YX301	SPO2	70%~100%	±2%

Physical environment measured during the experiment is depicted in Table 3. Air velocity was controlled below 0.1m/s. According to ASHRAE Standard 55-2017 [40], operative temperature is the average of air temperature and mean radiant temperature. As shown in Table 3, air temperature was almost equal to globe temperature. Therefore, operating temperature can be considered consistent with the settings.

Table 3

Physical parameter measurements (mean value ± standard deviation).

Design condition(°C)	Air temperature (°C)	Relative humidity(%)	Globe temperature(°C)	Acoustics (dB(A))
28	27.9（0.2）	58.1（6.4）	28.0（0.6）	44.2（3.3）
26	25.9（0.3）	57.1（8.7）	26.1（0.6）	42.8（3.2）
24	23.9（0.2）	55.2（5.2）	23.9（0.6）	44.4（3.5）
22	22.1（0.3）	53.3（6.3）	22.2（0.7）	42.9（2.9）
34	34.9（0.2）	54.1（6.6）	34.2（0.5）	46.1（3.8）

2.5 Subjective perception

Questionnaires were applied to assess participants' thermal perception, workload and mood during the experiment, and the rating scales used in the experiment were ordinal. The thermal perception questionnaire consists of TSV, thermal comfort vote (TCV), thermal acceptance vote (TAV), and thermal preference vote (TPV) [40], which was recorded using a quantified Chinese version scale, and the scale of questions is shown in Fig. 2. A fine-grained thermal acceptance vote was selected to show the changes under different conditions. In the thermal preference scale, "lower" means prefer cooler and "higher" means prefer warmer.

National Aeronautics and Space Administration Task Load Index (NASA-TLX) is considered to be a valid measurement of subjective workload, with the highest user acceptance and minimal inter-subject differences. The rating scale of NASA-TLX is shown in Fig. 3, and it is a multi-dimensional approach to self-reported assessment that provides an estimate of overall workload associated with task performance and mental effort [42]. The overall workload score is a weighted average score of six basic psychological factors, including physical demand, mental demand, temporal demand, performance, effort, and frustration level.

Chinese version scales of Profile of Mood States (POMS) was applied to investigate the mood of participants for an experiment experienced. POMS is composed of seven mood states, including tension, depression, anger, vigor, fatigue, esteem-related affect and confusion, which is described by 40 adjectives [43]. Participants were asked to score their feelings on a 5-point Likert scale (from 0 (nothing at all) to 4 (complete)), and total mood disorder is equal to the sum of five negative mood scores minus the sum of two positive mood scores and plus 100.

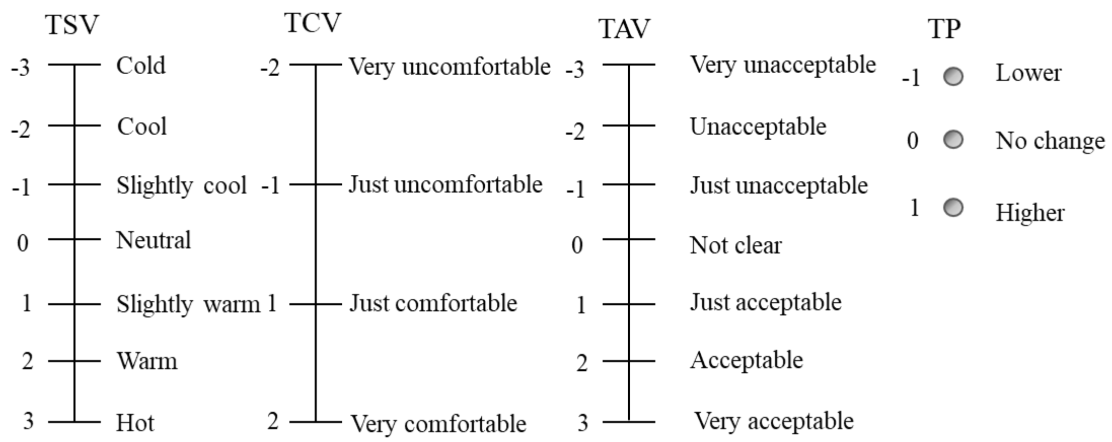


Fig. 2 Rating scales of thermal perceptions

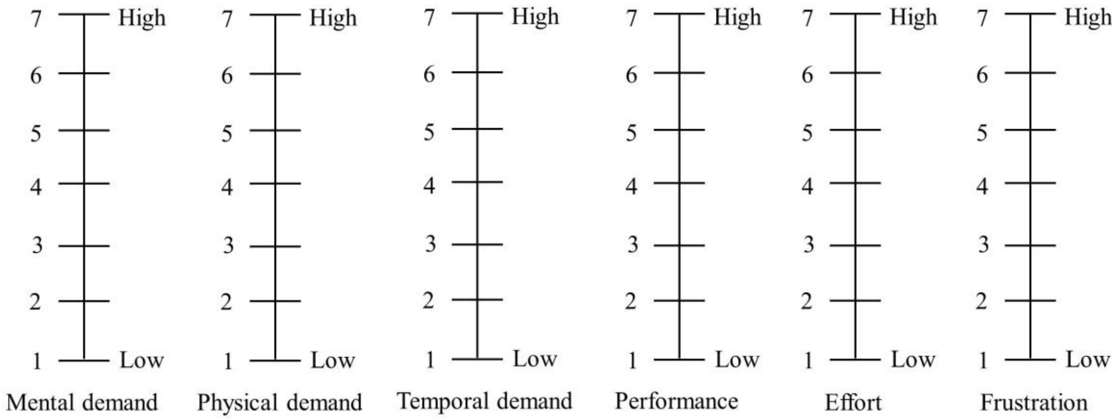


Fig. 3 The rating scale of NASA-TLX

2.6 Physiological measurements

The physiological instruments are illustrated in Table 2, and they meet the measurement accuracy requirements of ISO 9886 [44]. BP and HR were measured by wrapping the cuff of the upper arm sphygmomanometer around the participant's left arm. Oximeter was clamped on the middle finger of participants' right hand to measure SPO2. Oral temperature was measured as T_{cr} using sterilized electronic thermometers. According to ISO 9886, oral temperature is a satisfactory representative of T_{cr} when the ambient temperature is greater than 18°C [44]. The transducer was placed underneath the tongue, and subjects were asked to close their mouth during measurement. Skin temperature was not included in this experiment due to the equipment limitation. The selected physiological indicators change with the physiological regulation of body after the experience of temperature steps, and are related to people’s cognitive performance [13, 16, 45].

2.7 Learning performance tests

Learning performance can be reflected by cognitive ability, which refers to the process of people acquiring and applying knowledge, or the process of information processing [46]. Four categories of cognitive skills which are attention, memory, perception and thinking were tested [46], and two typical cognitive tasks were selected for each skill.

For attention skill, Simple Attention Blinking [47] (a1) required participants to find and memorize a red letter and the following letter from a series of letters; Test of Variables of Attention [48] (a2) asked participants to focus on and respond to the top square that appeared on the screen. For memory skill, Digital Span [49] (m1) was used to test verbal working memory through a sequence of numbers; Serial Probe Recognition [50] (m2) was applied to test visuospatial working memory by a sequence of flashing boxes. For perception skill, Stroop [51] (p1) required participants to indicate the color of the word on the screen; Visual Search [52] (p2) asked participants to check letter arrays of green and red L's and T's, and determine if there was a target. For thinking skill, Sequence of Baddeley's 3-minute Grammatical Reasoning Test [53] (t1) was applied to measure grammatical reasoning ability of subjects by judging whether letter pairs correctly represented the statements; Number Bisection [54] (t2) was used to measure mental arithmetic ability through determining whether the center number was the arithmetic mean of the other two numbers. Each participant sat in a fixed position and used the inquist5 software [55] to complete all tasks on laptops. Tasks were adapted from the paradigm downloaded from the Millisecond Test Library [55], and the amount of questions were modified to ensure that participants could complete the test within the limited time. The questions pre-programmed by the software are automatically presented on the computer screen, and the subjects could use the mouse/keyboard to answer.

In order to evaluate the results of cognitive test, two indicators identical to Lan [38], accuracy and reaction time were selected for most cognitive tasks. However, for Digit Span, maximum length and mean span are more suitable indicators, and the detailed calculation process can be referred to [51]. To access overall performance, a learning performance index was applied by integrating accuracy and reaction time with geometric weighting, as shown in formula (1) [45].

$$\text{Learning performance} = (\text{accuracy}^{0.5} \times (1/\text{reaction time})^{0.5})^2 = \text{accuracy} \times (1/\text{reaction time}) \quad (1)$$

To compare the relative performance of participants under different thermal conditions, formula (2) was used to standardize the test result, where $P_{i,j}$ is the learning performance of the i_{th} participant under the j_{th} thermal condition, and n is the number of thermal conditions developed [45].

$$\textit{Relative performance (\%)} = nP_{i,j} / \sum_{j=1}^{n} P_{i,j} \times 100\,\% \qquad (2)$$

2.8 Experimental procedure

The experiment was conducted in June, 2019, which began at 3:00pm and lasted for 105 minute. All participants were asked to avoid caffeine, alcohol and strenuous physical activity for at least 12 hours before the experiment, and to refrain from eating and drinking for one hour before the experiment. The experiment consisted of three stages (Fig. 4). To begin with, participants stayed in Room1 (26°C) for half an hour to rest and eliminate the influence of thermal experience before the experiment. They were allowed to chat or read after the staff reconfirmed the items that need attention during the experiment. Participants' physiological indicators (including BP, HR, T_{cr}, SPO2) were measured during the last four minutes in Room1. They were asked to fill out a thermal perception questionnaire before the physiological measurement. The same questionnaire survey and physiological measurement was done during 30-35 minutes, 45-50 minutes, 50-55 minutes, and 95-100 minutes. In Room2 (34°C), they walked for 10 minutes at a pace of 80-100 steps/min to simulate outdoor activities before class. Finally, they entered Room3 (22-28°C) and stayed there for 55 minutes. Learning performance test began after the thermal perception questionnaire and physiological measurement, and consisted of eight tasks. Every task was followed by a NASA-TLX questionnaire. An additional thermal perception questionnaire was conducted after they entered Room3 for 25 minutes. At the end of the experiment, participants spent another 5 minutes filling out a POMS questionnaire. As the main focus of this study was the effect of temperature steps on students' subjective perception, physiological response and learning performance, other confounding factors were controlled as much as possible in the experiment design. For example, the participants had fully understood the experimental procedure during the pre-experiment.

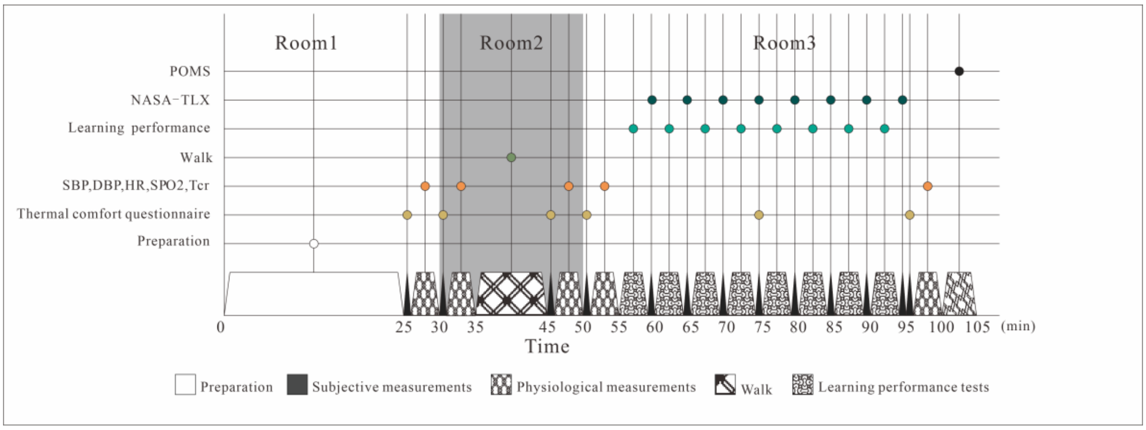


Fig. 4 Procedure of the experiment

The within subject design and Latin square design were applied to reduce the influence of individual differences and sequence effects on experiments [56]. The sixteen participants were assigned to four groups, and each group consisted of two males and two females. A group of members participated in an experiment at a time, and the order of the four groups exposed to the four experimental conditions was balanced by 4×4 Latin-square design. Considering that the temperature step effect may change over time, the rule was also applied to the order of four cognitive skills for participants.

2.9 Statistical analysis

SPSS 23.0 was used to analyze the data. The normality of data was tested through Shapiro-Wilk test. When data was normally distributed or similarly skewed distributed, ANOVA was conducted to analyze the effect of thermal environment. Otherwise, Friedman, Wilcoxon, and kruskal-wallis H tests were applied. Significance level of the above tests was set at 0.05, and the results were statistically significant when $P < 0.05$. In addition, regression analysis was exploited to investigate the relationship between learning performance and thermal conditions.

3. Result and discussion

3.1 Subjective perception

The results of thermal perception in response to temperature steps are depicted in Fig. 5. When entering Room3 from Room2, TSV declined markedly, while TCV, TAV and TPV increased significantly. The TSV in Room3 showed significant differences among the four thermal conditions

(P<0.001). After entering Room3, thermal neutrality was observed at about 28°C within 1 minute and approximately 26°C at 25 and 45 minutes. As participants just experienced high temperature exposure, a slightly warm thermal environment (28°C) made them have the "illusion" of thermal neutrality, which also confirms the findings of studies [12, 17, 18]. When the temperature step was no more than S10, TSV did not show a significant change after 25 minutes. For the four environment settings, participants felt the most comfortable when Room3 was set to 26°C. The result of TAV was similar to that of TCV, with 26°C being the most acceptable environment for participants. In addition, it was observed that TAV almost unchanged within 25 minutes, but decreased significantly in the following period when the temperature step was S12, which was consistent with the result of TSV. The results of TPV indicated that participants preferred a temperature between 24°C and 26°C in Room3. When the temperature step was S6, participants had a strong desire to lower the temperature in the first 25 minutes, and this willingness noticeably weakened in the last 20 minute. The "slightly warm" environment (28°C) could not provide sufficient cooling during the recovery phase [19].

Since indoor thermal environment is supposed to be acceptable for more than 80% of occupants [35], the change of TAV percentage after temperature steps in Room3 was analyzed, as shown in Fig. 6. The percentages of "Unacceptable" and "Just unacceptable" were considered as the proportions of participants who did not regard the thermal environment as acceptable. When participants voted for the first time after entering Room3, the proportions were 18.75% and 6.25% at 22°C and 24°C, respectively. After 25 minutes, the percentage of "Just unacceptable" changed from 0 to 12.5% when the temperature of Room3 was 28°C. For the last vote, it is worth noting that the sum of the "Just unacceptable" and "Unacceptable" ratios reached 37.5% for a temperature setting of 22°C. In the study of Zhang et al. [32], about 88% of the subjects who did not experience a temperature step deemed that a thermal environment of 22°C was acceptable. The difference in acceptability rates is accordance with the findings in the study [10], in which participants found that the low temperature environment that was originally considered acceptable became unacceptable after experiencing high temperature environment. The difference is attributed to human adaptation ability to thermal environment, and is exacerbated by sweat from activity in our experiment. In this regard, a slightly cool to cool environment could not only waste energy but also deteriorate thermal perception. As shown in Fig. 6, there were no “Unacceptable” or "Just unacceptable" votes when Room3 was set to 26℃.

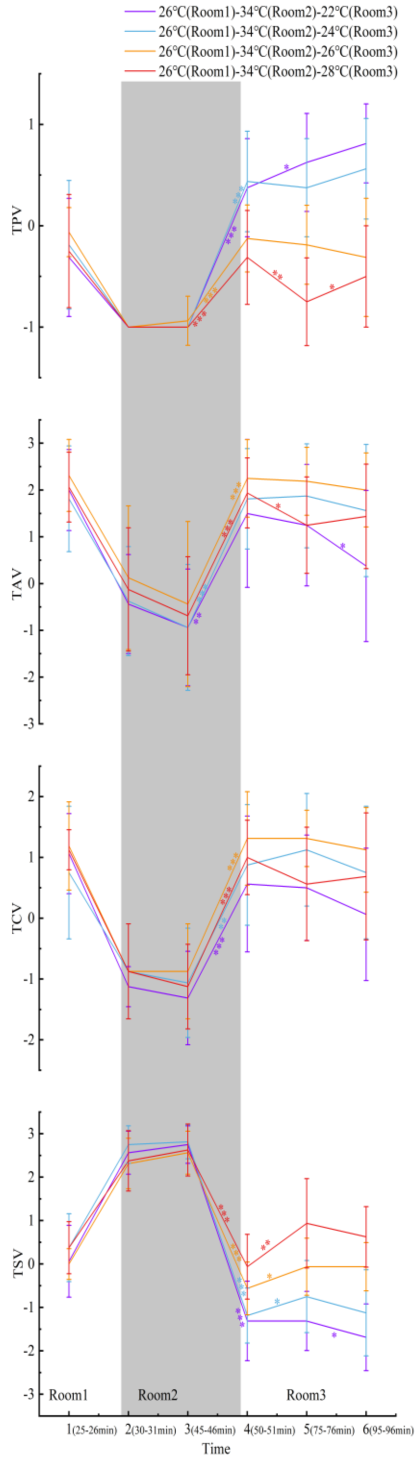
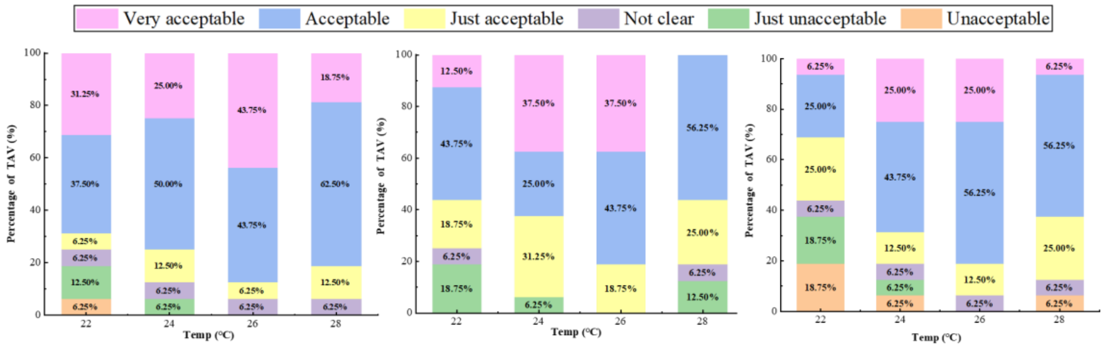


Fig. 5 Variations of TSV, TCV, TAV and TPV under temperature steps

(*P < 0.05, **P< 0.01, *** P < 0.001).



(A) 50-51min (B) 75-76min (C) 95-96min

Fig. 6 Percentage of TAV at (A)50-51min, (B)75-76min, (C)95-96min.

Fig. 7 presents the overall workload and six subscales of each cognitive task under the four conditions. For attention-related tasks, the physical demand of a1 at 22°C was significantly lower than that at 24°C and 28°C ($p<0.05$). The mental demand of a2 at 22°C was significantly lower than that at 24°C ($p<0.01$), and the performance of a2 at 22°C was significantly higher than that at 28°C ($p<0.05$). For perception-related tasks, the overall workload of p2 at 22°C was significantly lower than that at 26°C ($p<0.05$), and a lower temperature environment required less effort ($p<0.05$). As for thinking-related tasks, the mental demand of t2 was significantly lower at 22°C than at 28°C ($p<0.05$),while participants felt more frustrate at 24°C. As a whole, attention-related tasks appeared to be more susceptible to thermal environment. However, the effect was not significant in most cases, especially for memory-related tasks. This is not different from the results in a stable environment, and the workload mainly depends on the task difficulty [57].

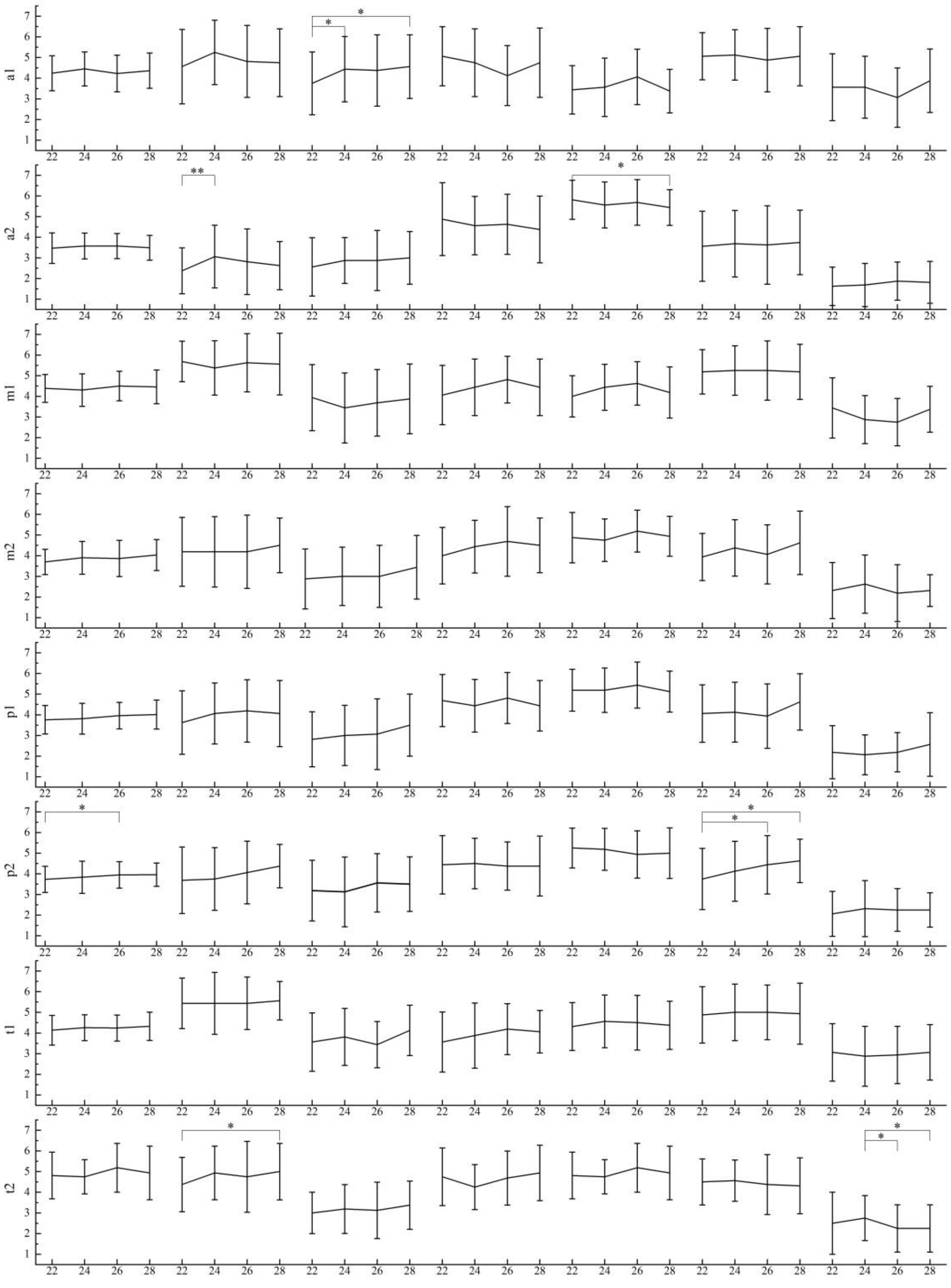


Fig. 7 Overall workload and the six subscales under the four thermal conditions

(*P < 0.05, **P< 0.01, *** P < 0.001).

The results of POMS under the four thermal conditions are presented in Fig. 8. The POMS questionnaire was the last step of the experiment and reflected mood states of participants throughout the experiment. For sub-items, higher scores of vigor and esteem-related affect indicate better mood state, while the other items are the opposite. When the temperature of Room3 was set to 26°C, all emotional factors of participants were better than other conditions except for fatigue. The sub-items showed no significant difference among the four thermal conditions. However, for total mood disorder, when the temperature of Room3 was set to 26°C, participants' negative moods were significantly less than 28°C and 22°C ($p<0.05$). Previous studies also found that a temperature step of 7-9°C may induce thermal pleasure for the discomfort caused by initial exposure [12, 15, 58].

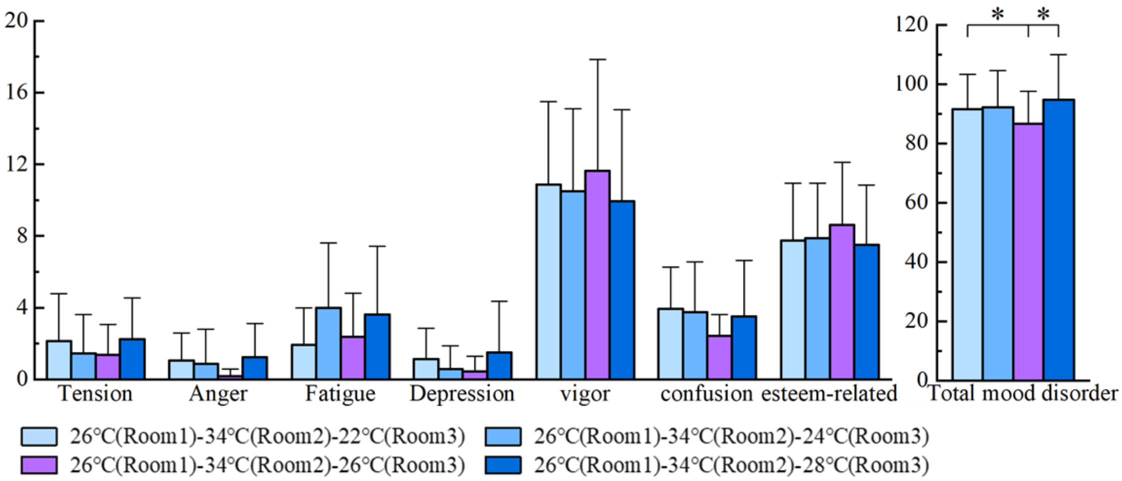


Fig. 8 Variations of subjective mood ratings in response to temperature steps

(*$P < 0.05$, **$P< 0.01$, *** $P < 0.001$).

3.2 Physiological measurements

Fig. 9 illustrates the fluctuations of systolic blood pressure (SBP), diastolic blood pressure (DBP), HR, SPO2 and T_{cr} during the experiment. When participants entered Room3 from Room2, DBP increased significantly when the temperature step was S12 ($p<0.05$). However, no significant change was observed for BP in other cases, which was different from the results of Xiong et al. [14]. One possible cause was the differences in the season studied, another more important reason to explain the discrepancy could be the magnitude of temperature steps. In [14], temperature steps for the three experimental conditions were S10, S20 and S40, respectively. As shown in Fig. 9, HR decreased significantly upon entering Room3 ($p<0.05$) and then reached a relatively stable state. Since the brain needs more oxygen for learning tasks, previous study observed an increase in HR after cognitive tasks [45]. In contrast, in our experiment, HR of participants decreased after the test in the four conditions, which is consistent with the results of studies on HR changes under temperature down steps [13, 19]. Therefore, it can be considered that the effect of temperature steps on HR was greater than that of cognitive test on HR during this experiment. After entering Room3, SPO2 increased in the four thermal conditions, but only increased significantly when the temperature step was S12 ($p<0.05$). As shown in Fig. 9, the value of SPO2 was always in the range of 95%-98%. T_{cr} measured during the first 5 minutes after experiencing the temperature step kept rising. Subsequently, it decreased during the test time, and decreased significantly when the magnitude of temperature step was greater than S8.

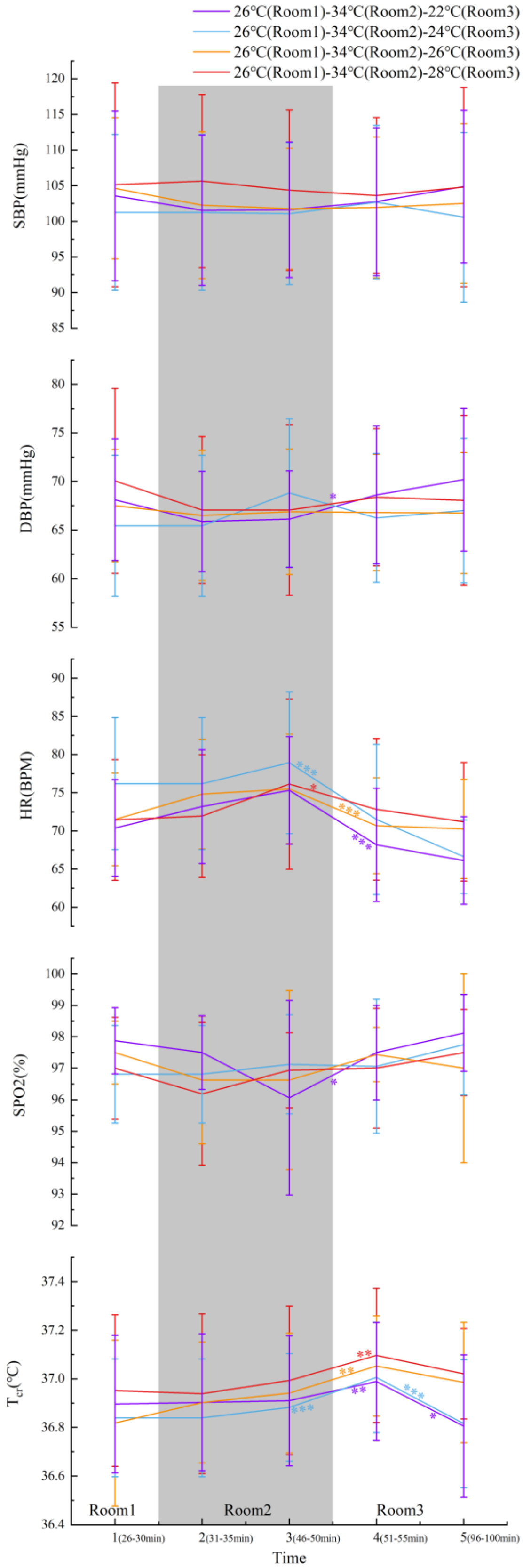


Fig. 9 Variations of SBP, DBP, HR, SPO2 and Tcr under temperature steps

(*P < 0.05, **P< 0.01, *** P < 0.001).

3.3 Learning performance

Physiological and psychological response is time-dependent after experiencing a temperature step [13, 19, 59], and this may also reflect on cognitive ability [25]. Bear this in mind, this study divided the cognitive test period (T: Test time) into two stages (T1: Time to do the first four tasks; T2: Time to do the last four tasks). As shown in Fig. 10, Fig. 11 and Fig. 12, as the temperature setpoint increases, the index of accuracy (refers to maximum length for task m1in Fig.10), reaction time (refers to mean span for task m1 in Fig. 11) and learning performance exhibits different trends among T1,T2 and T, which confirms the effect of temperature changes over time. Although learning performance was different under the four thermal conditions, results showed that there was no significant difference in cognitive ability. It may still be within the range of physiological and psychological zone of participants' maximal adaptability, which conforms to the extended U-shaped model [32, 60]. Similarly, Zhang and Richard [21] found that university students' cognitive performance remain unchanged under the temperature cycle of 21.3-31.2℃ induced by direct load control events. Within this range, the students could maintain near-optimal performance by consuming attentional resources. It is also in line with the results of NASA-TLX in our experiment, as attention-related tasks were observed to be more susceptible to thermal environment.

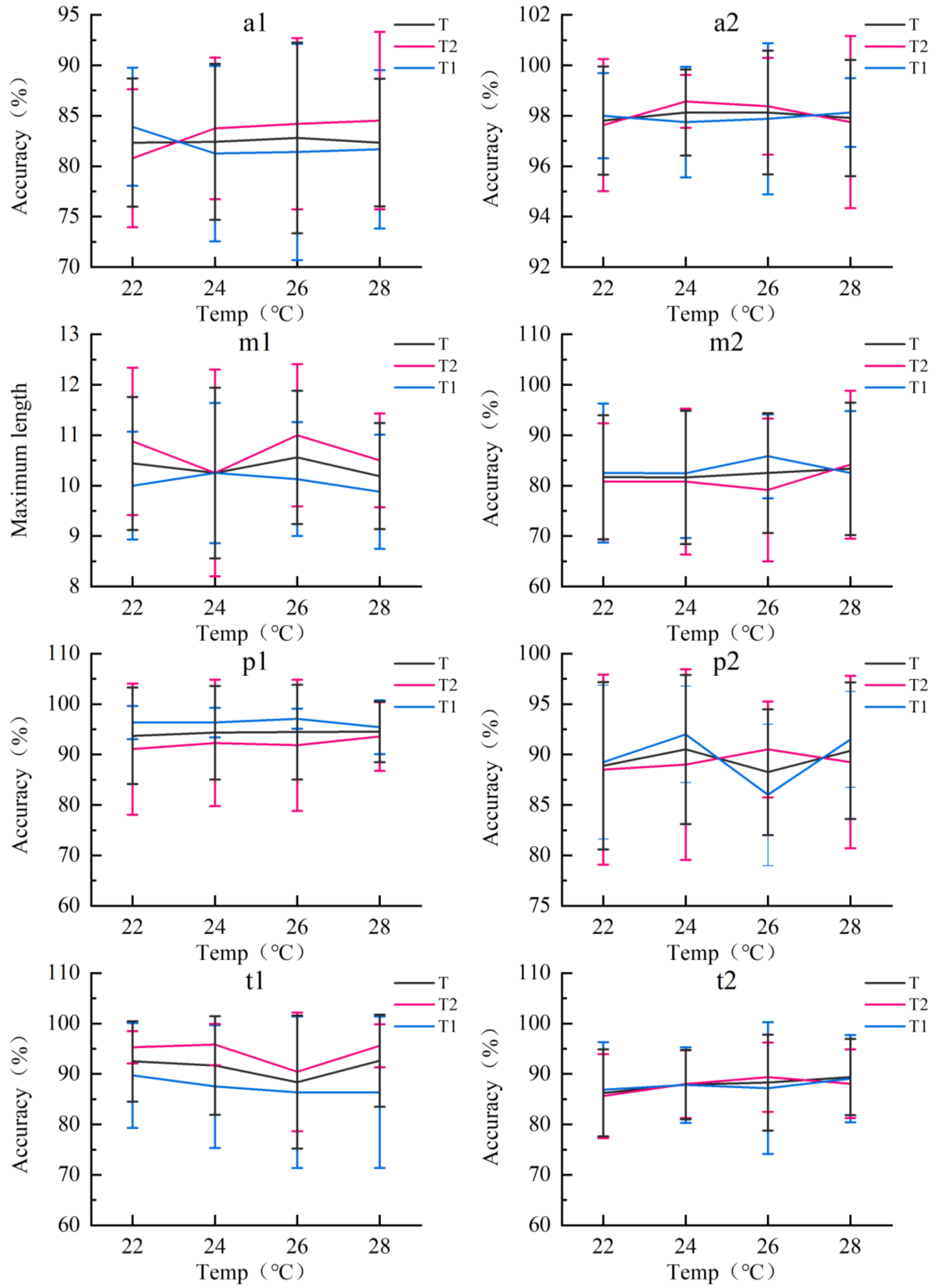


Fig. 10 Variations in the accuracy of learning performance tasks.

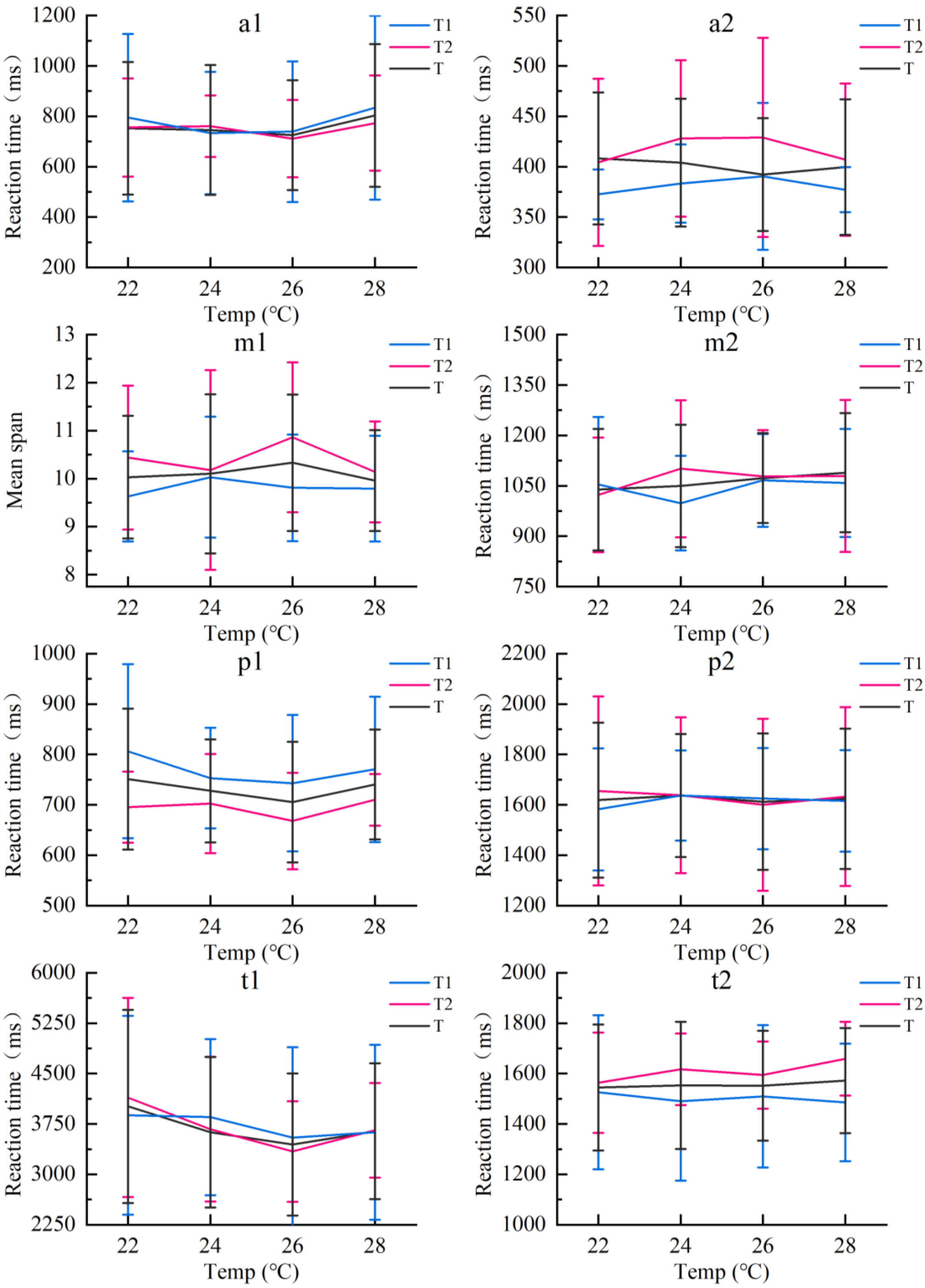


Fig. 11 Variations in the reaction time of learning performance tasks.

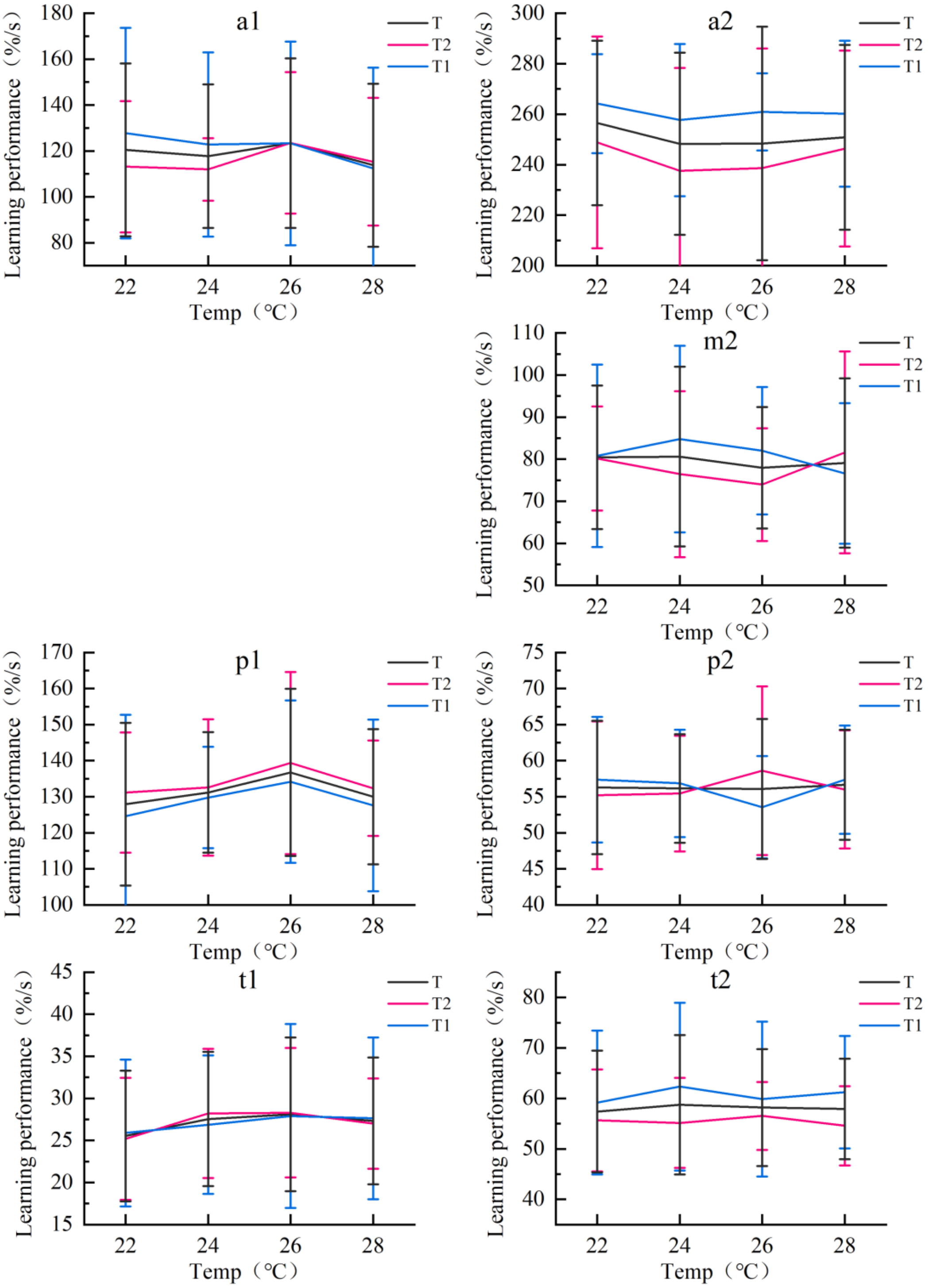


Fig. 12 Variations in the learning performance of learning performance tasks.

Learning performance was standardized to investigate the relationship between performance and temperature, as shown in Fig.13. The regression lines were generated based on the average learning performance under different conditions [25, 26, 45]. According to the functions, the optimal performance during T1 was found at about 24.4℃, while that in T2 was obtained at around 26℃. As far as the results of the entire test time are concerned, participants generally achieved the optimal performance at approximately 25.3℃. To compare with previous studies which were conducted in a steady thermal environment, the quantitative relationship between temperature and relative performance in different studies was presented, as illustrated in Fig. 13. The results showed that the optimal temperature for cognitive performance obtained in [23] is the lowest, which is about 22℃. The data set of [23] was derived from 24 studies that did not focus on Chinese subjects. Although the settings of indoor air temperature was similar, which ranged from 16℃ to 28℃ with a step of 2℃, the result of [25] was also lower than that of this study. In addition to the effects of temperature steps, two other possible causes were:1) the experiment was carried out in November, and physiological and psychological adaptability of participants could be affected by seasons; and 2) participants wore heavier clothing in the experiment (clo=1.15). In [26], the optimal performance was obtained at 26℃, which is similar to the result of T2 when the temperature step effect has subsided in this experiment.

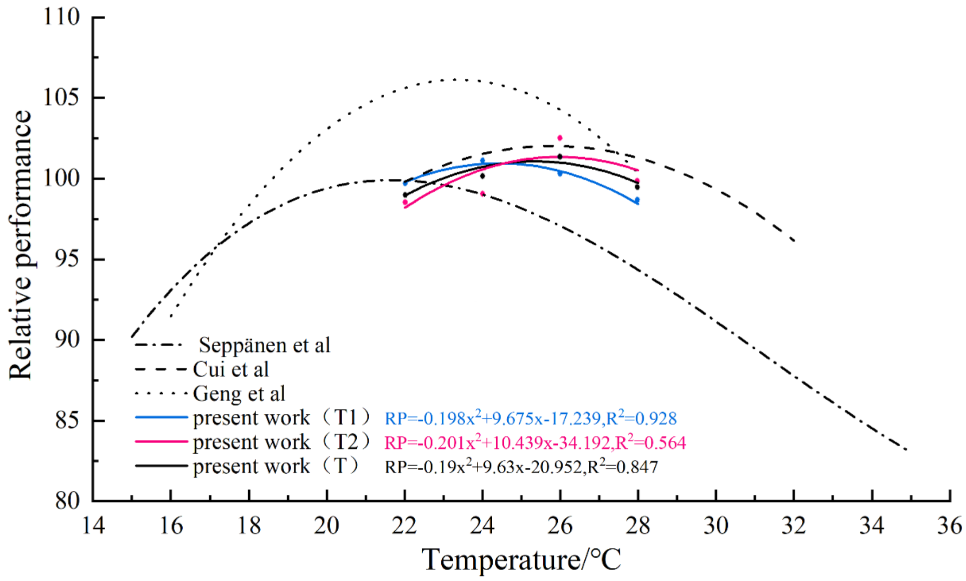


Fig. 13 Comparison of relationship between relative performance and temperature in this study with other studies by Seppanen et al. [23], Geng et al. [25], and Cui et al. [26] (T1: Time to do the first four tasks; T2: Time to do the last four tasks; T: Test time).

Since people have different adaptability to thermal environment, the relationship between TSV and relative performance was also investigated, as shown in Fig. 14. Participants performed best during T1 with a TSV of -0.87. In T2, the optimal performance was obtained when the TSV was close to 0.11. For the entire test time, the optimal performance was achieved when the TSV was approximately -0.4. In addition, it is observed that the relative performance in a cool or neutral environment is much higher than that in a warm environment. An increase in relative performance was obtained when TSV was close to -3, which was attributed to the fact that the effect of cold stimulation on reaction time was greater than that of cold stimulation on accuracy. Considering the experiment condition varies in different studies, the analysis of quantitative relationship between TSV and learning performance could provide more comparable inductions. As illustrated in Fig. 14, selected studies were conducted in China, and the samples showed similar relationship. In the study of Lan et al. [24], the best performance was obtained with a TSV of -0.25. In the study of Cui et al. [26], it was achieved with a TSV of 0.14. In the study of Geng et al. [25], it was achieved when the TSV was about 0. In our experiments, after participants experienced a temperature step, the corresponding TSV for the optimal performance was -0.87 in 25 minutes (T1), and 0.11 within 25 to 45 minutes (T2). It can be seen that the results in T2 are not much different from previous studies, while the results during T1 are relatively low. This is consistent with the relationship between temperature and learning performance, and a “slightly cool” environment is more conducive to students’ learning performance shortly after being exposed to high temperatures.

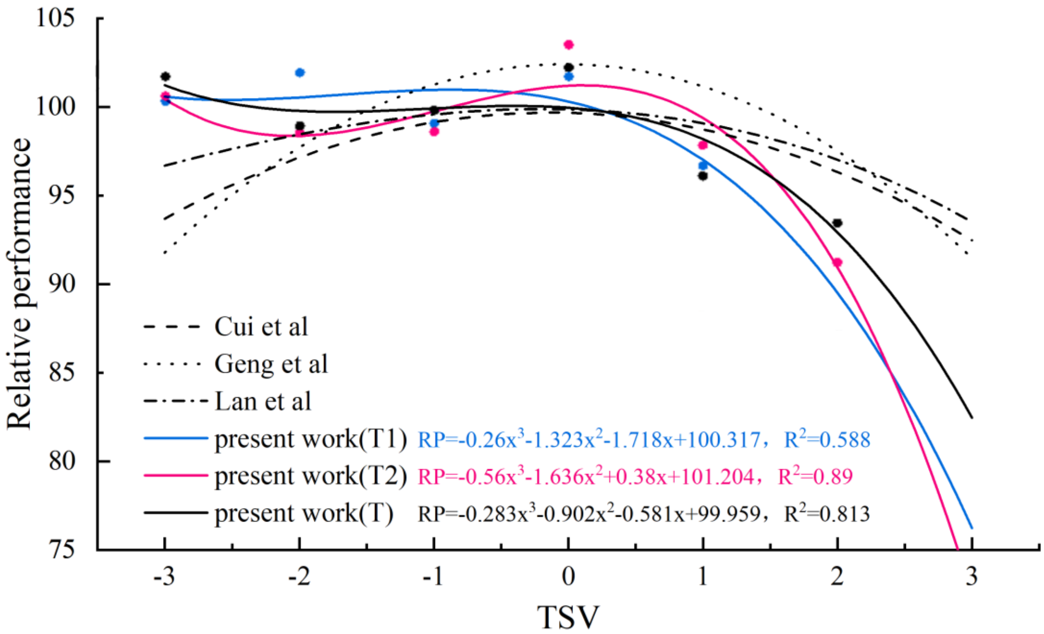


Fig. 14 Comparison of relationship between relative performance and TSV

in this study with

other studies by Lan et al. [24], Geng et al. [25], and Cui et al. [26]

(T1: Time to do the first four tasks; T2: Time to do the last four tasks; T: Test time).

3.4 Optimal thermal conditions

To explore the optimal thermal environment of classrooms in hot summer, the comprehensive effects of the four thermal conditions on students' subjective perception, physiological response, and learning performance were analyzed.

In terms of subjective perception, it was found that the thermal acceptability of students did not meet the requirements of indoor thermal environment when the temperature step was S12. In addition, participants felt the most acceptable and comfortable at 26°C after temperature steps. The effect of thermal environment on workload was not significant in most cases, especially for memory-related tasks. However, when the temperature was set to 22°C or 28°C, participants experienced more negative mood than 26°C. In this regard, the indoor temperature is preferably 26°C, but it is not recommended to set it to 22°C.

Physiological measurement reflects what extents the influence of different temperature steps on the human body. Results indicated that instant cold exposures can induce significant difference in SPO2 and BP when the temperature step was 12°C. Tcr of participants decreased during the test time, and decreased significantly when the magnitude of temperature step was greater than S8. However, in this experiment, due to the temperature steps and exposure time were relatively mild, the physiological variations modulated by thermal regulation system were within the normal range. For example, the value of SPO2 was always in the range of 95%-98%. Further research could be conducted to explore the relationship between short-term thermal environment stimuli and health.

As for learning performance, no significant difference was found after participants experienced the four temperature step conditions. For the entire test time, when temperature steps were S6, S8, S10, and S12, the relative performance were 99.73%, 100.99%, 100.73%, and 98.95%, respectively. The maximum difference between the four conditions is about 2%, which is smaller than the results obtained in a stable environment [25, 26]. As discussed in section 3.4, participants achieved their best performance at 24.4°C and 26°C in the two periods. It may not be necessary to lower the temperature in the first 25 minutes with additional energy consumption.

Overall, considering the impact of temperature steps on the three aspects equally, the optimal thermal condition is 26°C. The thermal conditions between 24-28°C are quite acceptable, which could be the recommended range for indoor temperature settings.

4. Conclusions

The experiment was conducted under four temperature step conditions (S6: 34°C-28°C, S8: 34°C-26°C, S10: 34°C-24°C, S12: 34°C-22°C), aiming to investigate the responses of students' subjective perception, physiological indicators and learning performance to temperature steps, and explore an optimal thermal condition for classrooms in hot summer.

(1) After temperature steps, no more than 62.5% of students consistently found thermally acceptable at 22°C. In addition, students felt the most acceptable and comfortable at 26°C. The

effect of thermal environment on workload was not significant in most cases, especially for memory-related tasks. In terms of mood, students' negative mood was less at 26°C than at 28°C and 22°C.

(2) Participants' physiological response was significantly related to the magnitude of temperature steps. When the temperature step was less than S12, BP and SPO2 appeared to be insensitive to thermal stimuli. T_{cr} continued to rise during the first 5 minutes and then decreased significantly when the temperature step was greater than S8.

(3) No significant difference in learning performance was found among the four conditions. The differences in relative performance between thermal conditions were less than 2%, and are not likely to have practical meaning in building management practice.

(4) Considering the overall effect of temperature steps on students' subjective perception, physiological response and learning performance, the optimal thermal condition is 26°C, and it is recommended to set the indoor temperature between 24-28°C.

While this study focused on relatively short-term physiological indicators, with the learning performance in two separate time periods, in future work, analysis with higher temporal resolution could be further carried out, as neurophysiological methods such as electroencephalogram could continuously record subjective perceptual changes [15, 32, 58].

Acknowledgements: This research is supported by National Natural Science Foundation of China (Grant No.71732001, No.51978302, No.51678265, No.71821001) and China Scholarship Council.

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