Cognitive performance was reduced by higher air temperature even when thermal comfort was maintained over the 24-28°C range

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Abstract. This study managed to create thermal comfort conditions at three temperatures (24°C-T24, 26°C-T26, and 28°C-T28) by adjusting clothing and air velocity. Thirty-six subjects (18 males and 18 females) were exposed to each of the three conditions for 4.5h in a design balanced for order of presentation of conditions. During each exposure, they rated the physical environment, their comfort, the intensity of acute subclinical health symptoms and their mental load and they performed a number of cognitive tasks. Their physiological reactions were monitored. The subjects rated T24 to be comfortably cool, T26 to be comfortably neutral and T28 to be comfortably warm. Their self-estimated performance did not differ between conditions but 12 of 14 objective metrics of cognitive performance decreased significantly at the elevated temperatures: compared with T24, their average cognitive performance decreased by 10% at T26 and by 6% at T28. At the elevated temperatures, their parasympathetic nervous system activity (as indicated by PNN50) and their arterial blood oxygen saturation level (SpO2) were both lower, which would be expected to result in reduced cognitive performance. The subjects also rated their acute subclinical health symptoms as more intense and their workload as higher at the elevated temperatures. These results suggest that where cognitive performance is the priority, it is wise to ensure a comfortably cool environment. The present study also supports the use of fans or natural ventilation to reduce the need for mechanical cooling.

Keywords: cognitive performance; physiological responses; elevated air temperature; thermal comfort; air movement

Practical applications

- The present study observed differentiated effects of air temperature on thermal comfort and cognitive performance: cognitive performance decreased, parasympathetic tone and blood oxygen saturation level were lower, SBS symptoms were negatively affected and subjective workload increased at higher temperatures even though thermal comfort was maintained over the 24-28°C range.
- The results suggest that optimal cognitive performance is not guaranteed by the attainment of thermal comfort. For spaces where cognitive performance is a priority, it is wise to ensure a comfortably cool

environment.

- Adding gentle air movement from a ceiling fan to increase the thermal comfort range upwards can reduce the negative effects of elevated air temperature on acute subclinical health symptoms, perceived air quality and cognitive performance.

1. Introduction

Thermal environment is one of the most important indoor environmental factors that affect human health, comfort and performance. Even moderate heat stress, caused by elevated indoor temperatures, has been shown to result in acute subclinical health symptoms such as headache, fatigue, and difficulty in concentrating [1-4], has produced higher sympathetic nervous system activity [1], and increased respiratory health problems [5]. Exposure to indoor temperatures above a 26°C threshold increased respiratory distress calls to emergency services (odds ratio=1.63, P=0.056) [5]. Elevated indoor temperatures reduced cognitive performance and learning performance in office workers, college students, and schoolchildren [3, 6-8], and this applies even to subjects who have become acclimatized to higher temperatures by living in tropical climates [9]. These findings suggest that, in addition to thermal comfort, it is necessary to examine the effects of the thermal environment on health and cognitive performance. Cedeño-Laurent et al. (2018) used a new term, thermal health, to describe the effects of the thermal environment on building occupants. Thermal health goes beyond thermal comfort and includes effects on health, performance and well-being [10].

The effects of the thermal environment on cognitive performance have been quantified with a dose-response relationship which describes the change of performance with air temperature [11]. However, air temperature is only one of the thermal environmental factors that influence thermal comfort. The other influential factors are mean radiant temperature, humidity, air movement and the activity level and clothing of the individual. Attempts have been made to describe the change of performance with thermal sensation [12]. These two relationships all follow a bell-shaped curve centred around the conditions that are optimal for performance defined either by temperature [11] or by thermal sensation [12]. They suggest that high air temperatures and thermal discomfort have negative impacts on cognitive performance, and that a comfortably cool environment and avoidance of even moderately elevated temperatures will create conditions that are optimal for cognitive performance.

It is not clear whether the negative effects on performance at elevated temperatures are caused by temperature, by perceived thermal discomfort or by both. To clarify this question, the authors investigated whether adjusting clothing to remain in neutral thermal comfort at a moderately elevated temperature would be sufficient to avoid negative effects on cognitive performance [13]. The results show that a moderately elevated room temperature reduces cognitive performance even when people report that they are thermally comfortable. This indicates that the effects of air temperature on cognitive performance must be differentiated from its effect on thermal comfort. The subjects of this study were Caucasians resident in the temperate climate of Denmark, so to determine whether the results are generally applicable the same experimental protocol would have to be replicated using subjects with different thermal experience.

Air movement is often considered desirable at higher temperatures. Building occupants often want more air movement rather than less, even when reporting a ‘neutral’ thermal sensation [14]. Accordingly, the range of indoor temperatures deemed acceptable for thermal comfort has been increased by stipulating increased air movement from fans and natural ventilation, for example in regulations such as ASHRAE Standard 55-2017 [15]. The positive effects of air movement on thermal comfort have been extensively reported, while the effects of air movement on cognitive performance have not been sufficiently investigated. Personalized ventilation (local air flow) improved self-estimated and objectively-measured cognitive performance at high room temperature and humidity [16]. The subjects were able to control the rate and direction of a personalized flow of clean air. Even the possibility of individual control might be expected to result in an improvement in cognitive performance.

In the present study, the subjects maintained thermal comfort and performed cognitive tasks at three air temperatures. The objective was to differentiate the effects of air temperature on thermal comfort from its effects on cognitive performance. Physiological responses were examined to elucidate the mechanisms for any changes observed. The overall goal of the experiment was to enable the building industry to overcome barriers to creating energy-efficient buildings of high indoor environmental quality.

2. Methods

2.1 Experimental conditions

The experiment was carried out in a low polluting, air conditioned office (8m*7m*3m) in Shanghai in July and August 2020. Shanghai has a hot humid summer climate; during the experiment the maximum outdoor daily temperature was from 29°C to 35°C (mean=33.0°C, SD=1.8°C). Six workstations were installed in the office. Each workstation consisted of a table, a chair, and a desktop computer. Three thermal conditions were created by setting the temperature at 24°C (T24), 26°C (T26) and 28°C (T28), which are all within the comfortable temperature range for air-conditioned environments according to the specification of standard GB 50736-2012 in China (Table 1) [17].

Table 1 Indoor design parameters of air conditioning area in summer

Category	Temperature(°C)	Humidity(%)	Velocity(m/s)
Ⅰ	24~26	40~60	≤0.25
Ⅱ	26~28	≤70	≤0.30

Clothing insulation and air movement were changed between conditions to allow the subjects to maintain neutral thermal comfort at the three temperatures. To determine the required clothing insulation level and air movement, a pilot experiment was performed; Table 2 shows the approximate clothing level and air flow adopted at the three temperatures. Other conditions such as the outdoor air supply rate (20 l/s.person), noise level and illuminance were the same in each condition.

Table 2 Clothing insulation and air flow at the three temperatures

Conditions	Clothing	Air movement
T24	Trousers, short-sleeved T-shirt, long-sleeved sweater, 0.7 clo	Ceiling fan OFF, <0.2 m/s
T26	Trousers, short-sleeved T-shirt, approximately 0.5 clo	Ceiling fan OFF, <0.2 m/s
T28	Trousers, short-sleeved T-shirt, approximately 0.5 clo	Ceiling fan ON, 1.0 m/s

2.2 Subjects

Thirty-six subjects participated in the experiments; Table 3 shows the average characteristics of the subjects. They were recruited by online announcement and were all Chinese students at the Shanghai Jiao Tong University. The subjects had lived in Shanghai for more than one year, did not have chronic diseases, asthma, allergy, hay fever or colour blindness, according to their responses to a questionnaire distributed to them during recruitment. None of them was examined medically.

Table 3 Basic information of the subjects

Sex	Number	Age	Height (cm)	Weight (kg)	BMI
Male	18	25.02±4.09	172.13±7.25	64.98±9.48	22.07±2.79
Female	18	23.51±4.42	162.14±5.32	52.04±9.53	21.78±2.89

Within-subject design, in which the same subject was exposed to each of the three conditions, was used in the experiment. The subjects were randomly divided into six groups, with six subjects per group. The six groups were exposed to the three conditions in a Latin-square design balanced for order of presentation of conditions.

During the week preceding the experiment, the subjects attended a practice and instruction session to familiarize them with the experimental procedure and to practice the cognitive tasks so as to reduce the expected effects of learning. Another purpose was to instruct the subjects to wear the required clothing by showing them pictures of typical clothing. The subjects were also instructed what not to do on the experimental day and on the day prior to each exposure (e.g., drinking alcohol, overexertion, late to bed).

All protocols were approved by the Ethics Review Board of Shanghai Jiao Tong University (No E20200018I) and conformed to the guidelines in the Declaration of Helsinki. Verbal and written informed consent were obtained from each subject prior to their participation in the experiment. The subjects were paid for participating in the experiment at a fixed rate per hour; they did not receive any bonuses related to their performance of the tasks. All subjects completed all three experimental exposures.

2.3 Measurements

During exposure in the room, the subjects performed tasks typical of office work and neurobehavioural tests designed to assess different cognitive skills. Physiological responses and biomarkers were monitored during the exposures. The subjects rated perceived air quality, thermal comfort, sweating, the intensity of the acute subclinical health symptoms sometimes termed Sick Building Syndrome (SBS) symptoms or Building-Related Symptoms (BRS), sleepiness, their workload and their performance, by marking visual-analogue scales.

2.3.1 Physical measurements

The temperature, relative humidity, and concentration of CO2 in the office were continuously recorded with data loggers (TR-76Ui, T&D corporation) at each of the six workstations and at the centre of the room. The data logger had a built-in CO2 sensor (range: 0-9999pm, accuracy: ±50ppm+5% of reading at 5000ppm or less), a temperature sensor (range: 0°C-55°C, accuracy: ±0.5°C), and a humidity sensor (range: 10-95%, accuracy: ±5%). At the beginning of each experimental session and before the subjects entered the office, the air velocity at the six workstations was simultaneously measured with anemometers (Swema 03+ETR, range: 0.05-3.00m/s, accuracy: ±0.04m/s). The background noise in the occupied office was approximately 45 dB(A).

2.3.2 Cognitive performance

The subjects performed tasks typical of office work and neurobehavioral tests; they were presented on a desktop computer and were similar to those used by Lan et al. (2011a; 2020) [3, 13]. The tasks typical of office work included *Text typing* and *Addition*. Seven neurobehavioral tests were presented to subjects in the following order: *Mental redirection* (a spatial orientation test), *Grammatical reasoning* (a logical reasoning task), *Digit span* (a traditional test of verbal working memory), *Visual learning* (a picture memory task measuring spatial working memory), *Number calculation* (a mental arithmetical test in which the subject has to add and subtract two-digit numbers), *Stroop* (a test of the attentional focus and flexibility required to overcome perceptual/linguistic interference), and *Visual reaction time* (a sustained attention task measuring speed and accuracy in response to visual signals. A performance index (PI) was computed separately for each task to describe the mean processing/reaction time divided by the accuracy of responses (e.g., correct characters typed per minute or correct units added per minute). For *Digit span*, the PI was the maximum number of digits the subject could correctly learn and recall. *Text typing*, *Addition*, *Stroop*, and *Number Calculation* were additionally presented to subjects with feedback about their performance, i.e., they could not continue until they corrected the error [18]. In this case the PI was calculated as the reciprocal of processing/reaction time.

Different versions of the Tsai-Partington test were presented to the subjects to measure their cue-utilization capacity [19]. The Tsai-Partington was a pen-and-paper test. The number of correct links completed was used as an index of the reduced cue-utilization that is expected when arousal increases.

2.3.3. Physiological responses

Skin temperature. The face has been shown to be a highly thermosensitive area for both perceptual thermal sensitivity and autonomic sensitivity, compared to other locations across the body [20]. Skin temperature at the forehead was measured continuously to reflect the thermal state of the body, at an interval of 1 min, using a wireless sensor (Pyrobutton, USA, range: -20°C to +85°C; accuracy: ±0.3°C; resolution: 0.0625°C). The wireless sensors were attached to the skin by two layers of medical adhesive tape with good air permeability.

Heart rate and heart rate variability (HRV). A cardiac signal was recorded throughout the exposure with a portable electrocardiograph (CCS-103, Careshine Electronic Technology Ltd). HRV refers to the variation in the time interval between adjacent heartbeats and represents one of the most promising indicators of the activity of the autonomic nervous system. HRV may be evaluated with either time-domain or frequency-domain methods. pNN50, the percentage of successive heartbeat intervals that differed by more than 50 ms, is a time-domain measure of HRV. A higher pNN50 indicates higher levels of parasympathetic nervous system (PNS) activity [21]; higher PNS activity has been shown to be an indication of lower stress and increased cognitive capacity [22,23]. Frequency-domain measurements estimate the distribution of power into four frequency bands, including ultra-low-frequency (ULF), very-low-frequency (VLF), low-frequency

(LF), and high-frequency (HF) bands. The ratio of LF to HF (LF/HF) reflects the balance between the sympathetic nervous system (SNS) and the PNS. The LF/HF value has been shown to be associated with thermal comfort and is approximately 1 when subjects feel thermally comfortable [24].

Peripheral oxygen saturation (SpO2). SpO2 is an estimation of the blood oxygen saturation level and indicates the percentage of haemoglobin molecules in arterial blood that are saturated with oxygen. Healthy individuals at sea level usually exhibit oxygen saturation values between 96% and 99% and the value should remain above 94%. SpO2 was measured with a pulse oximetry instrument (PC-68B, Lepu Medical, China; range: 35-99%, accuracy: ±2%) using an infrared sensor attached to the subject`s finger. Higher oxygen saturation is associated with improved cognitive performance [25, 26].

Salivary alpha-amylase (sAA). sAA is a biomarker for stress-related changes and reflects the activity of the sympathetic nervous system [27]. For healthy adults under no stress the salivary amylase value thus measured is less than 30 kIU/L; 31-45 kIU/L suggests a low level of stress, 46 to 60 kIU/L moderate stress, and higher levels indicate severe stress. A non-stimulated passive drool salivary sampling procedure was applied, in which the subjects were asked to expel saliva into a labelled sampling tube for about 5 min to provide about 4 ml of saliva. They were asked not to eat or drink for half an hour prior to the collection of saliva. The saliva samples were centrifuged for 25 min at 4000 rpm and stored in a freezer at -20°C before being sent for analysis. The sAA activity was analysed by an external specialized laboratory using enzyme-linked immunosorbent assay kits (range: 50 IU/L – 1600 IU/L, minimum detectable does: 12.5 IU/L). The intra-assay variation and the inter-assay variation were below 5%.

2.3.4 Subjective assessments

A subjective questionnaire included questions regarding thermal comfort, perceived air quality, SBS symptom intensity, and subjective sleepiness. The questionnaires used were similar to those used by Lan et al (2011a, 2020) [3, 13]; they were presented to the subjects on paper.

Thermal comfort. The ASHRAE 7-point continuous scale was used to register thermal sensation: hot (3), warm (2), slightly warm (1), neutral (0), slightly cool (-1), cool (-2), cold (-3). Thermal comfort was assessed using a continuous scale: very comfortable (2), comfortable (1), just comfortable (0.1), just uncomfortable (-0.1), uncomfortable (-1), very uncomfortable (-2). The acceptability of the thermal environment was assessed using the DTU split scale on which a mark must be placed either somewhere between the semi-scale end-labels “Clearly acceptable” and ”Just acceptable” or between “Just not acceptable” and ”Clearly not acceptable” [28]. This forces the subject to make a binary “acceptable/not acceptable” decision as well as a visual-analogue rating of the degree of acceptability.

Sweating. The subjects reported their perception of sweating using a 5-point scale: no sweating (0), no sweating but skin feels sticky (1), sweating slightly (2), sweating (3), sweating freely (4).

Perceived air quality (PAQ). The participants reported their perception of indoor air quality and odour intensity using DTU continuous visual-analogue scales [28].

SBS symptom intensity. The intensity of self-assessed acute subclinical health symptoms and willingness to perform work were rated using visual-analogue scales (VAS) - horizontal lines without graduation with two vertical dash lines marking the extreme points of the scale, each with end labels [28].

Sleepiness (SLP) and self-estimated performance. Sleepiness was assessed using the 9-point verbally anchored Karolinska Sleepiness Scale with the following steps: extremely alert, alert, neither alert nor sleepy, sleepy but not fighting sleep, and very sleepy - fighting sleep [29]. Subjects reported their self-estimated performance and their willingness to perform work using ungraduated visual-analogue scales (VAS). The position of the mark was determined on a scale of 0-100, with 0 indicating low and 100 indicating high.

Workload. The NASA Task Load Index (TLX) for evaluating workload was derived using responses to the questionnaire described by Hart and Wickens (1990) [30]. It was determined from the responses on six linear scales (similar to VAS) describing “mental demand”, “physical demand”, “temporal demand”, “performance”, “stress”, and “frustration level”. The endpoints of the scales were marked low and high, except that in the case of performance (self-estimated performance of the tasks performed) they were marked poor and good (corresponding respectively to low and high). The overall mental workload was calculated by averaging the scores on the six component scales.

2.4 Experimental procedure

Figure 1 shows the schedule for each experimental session. The experiments took place between 1:00 and 5:30 p.m.; subjects arrived at the laboratory about 20 min before each exposure. The sensors used for measuring skin temperature and the cardiac signal were attached when they arrived. The subjects then entered the office, approached their workstations and provided saliva samples immediately. Their SpO2 was measured and they then rated thermal comfort and perceived air quality. They performed a multiplication task for 15 min; this period allowed subjects to adapt to the office condition and their performance of the multiplication task was not analysed. After this adaptation period, the subjects again provided saliva samples and then rated thermal comfort, perceived air quality, and the intensity of their acute subclinical health symptoms. Subjects then performed a 3-min Tsai-Partington test followed by a period of 40 min during which they performed tasks typical of office work. Upon completing the tasks, subjects evaluated their workload on the NASA-TLX questionnaire. This was followed by a period of 40 min during which they performed neurobehavioural tests. They then rated thermal comfort, perceived air quality, sleepiness, and the intensity of acute subclinical health symptoms. After these responses, the subjects took a 10 min break during which they could leave the office but were asked to stay inside the building. The above task block was repeated after the break. Toward the end of the exposure, the subjects performed a 3 min Tsai-Partington test, their SpO2 was measured, they provided saliva samples for the third time, and then rated thermal comfort, perceived air quality, sleepiness, and the intensity of acute subclinical health symptoms.

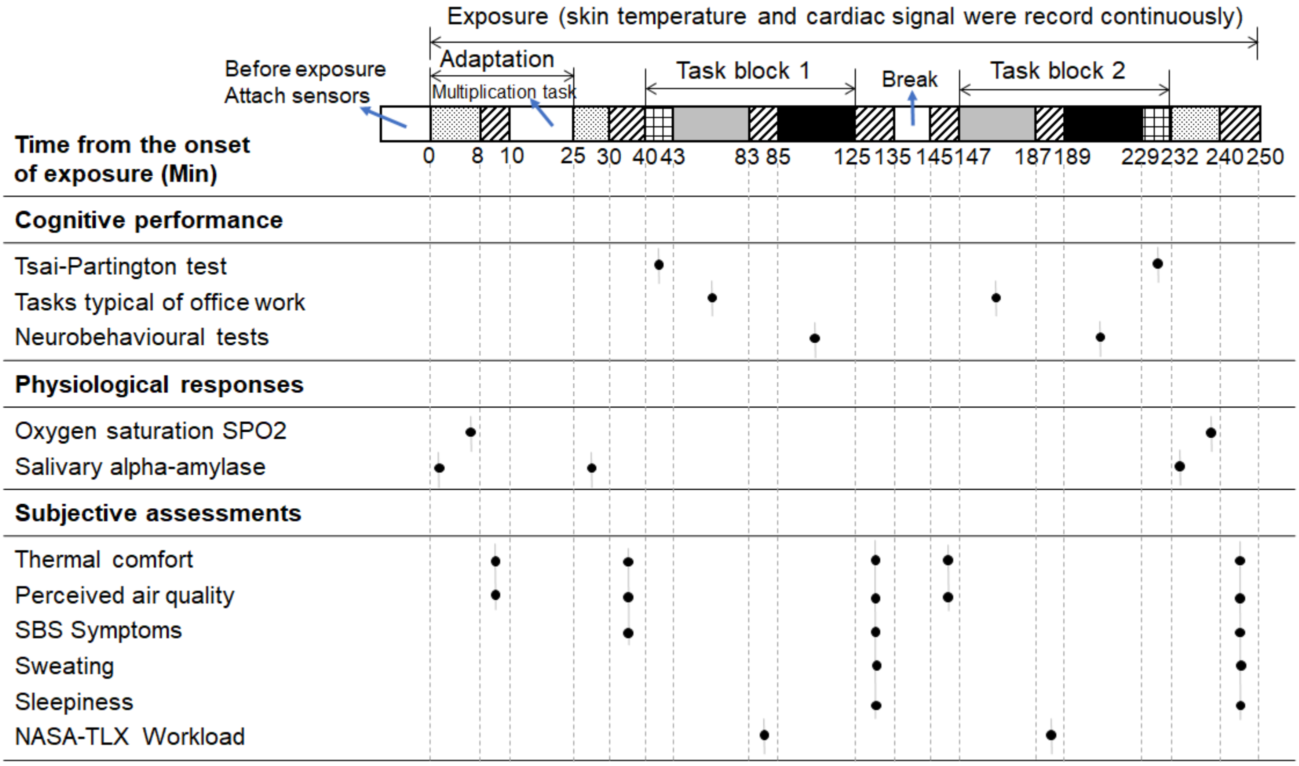

Figure 1 Experimental procedure

2.5 Data analysis

The IBM SPSS Statistics 21 software was used to perform the statistical analysis. The data were subject to analysis of variance (ANOVA) with a General Linear Model (GLM) in a repeated measures design. If multiple measurements were made throughout the exposure, the effects of exposure were analysed by setting thermal condition and exposure time (or block of tasks, as indicated in Figure 1) as the two within-subject factors. Huynh–Feldt statistics was used to adjust the violation of sphericity. The significance level was set to be 0.05 ($P<0.05$). An LSD test was performed when the ANOVA indicated that the main effect of thermal condition was significant ($P<0.05$). The effect size (ES), the difference between the true value and the value predicted by the Null Hypothesis, was derived as an indicator of whether the difference was of any practical importance [31]. For effect sizes based on differences between means, Cohen's d values (referred to as *d*) of 0.2, 0.5, and 0.8 are defined as small, medium, and large, respectively; for effect sizes based on "variance explained", i.e., F tests, Cohen's f (referred to as *f*) of 0.1, 0.25, and 0.4 are defined as small, medium, and large, respectively [32]. With Equation (1), Cohen's f was calculated from partial eta squared, which is the output of GLM ANOVA.

$$f = \sqrt{\frac{\eta^2}{1-\eta^2}} \qquad (1)$$

3. Results

3.1 Physical parameters

Table 4 shows the averaged physical parameters under the three conditions. The air temperature and air velocity were successfully controlled and remained very close to the intended values. The CO_2 concentration shown in Table 4 are averaged values during the period when they were stable (Figure S1); although the differences in CO_2 value between the three conditions are small, the CO_2 concentration was consistently lower at T24 than at T26 ($P<0.01$) or at T28 ($P<0.05$). However, average CO_2 values below 750 ppm indicate that the office was well ventilated under all three conditions. Relative humidity (RH) and illuminance at desk level were similar among the three conditions.

Table 4 Results of environmental parameters under the three conditions (mean ± standard deviation)

Conditions	**T(°C)**	**RH(%)**	**CO_2(ppm)**	**Velocity (m/s)**	**Luminance (lx)**
T24	24.2±0.1	66±2	715±42	0.11±0.15	790±150
T26	26.4±0.1	59±1	748±48	0.08±0.12	810±180
T28	28.3±0.1	62±1	737±52	1.02±0.25	750±210

3.2 Cognitive performance

Cognitive performance scores at the three thermal conditions are shown in Figure 2 and Table 5. In Figure 2, the relative performance of each task is shown by calculating a z-score for the Performance Index (*PI*) of each subject (Equation 2). Figure 2 shows that there was a similar trend in performance for most tasks, i.e., the *PI* was highest at T24 and lowest at T26. The *PI* of *Tsai-Partington* and *Numerical calculation with feedback* test decreased with higher temperature, but as shown in Table 5, no significant difference in the *PI* of these two tasks was observed between T26 and T28, at which the *PI* of both tasks was significantly lower compared with T24. Table 5 shows that significant differences in the performance of most tasks were observed between the conditions. With the exception of the *Grammatical Reasoning* task, the performance of the tasks decreased significantly at T26 and T28 compared to T24. The performance of several tasks was significantly lower at T26 than at T28. The performance of the *Grammatical Reasoning* task was also lower at T26 than at either T24 or T28, although no significant difference could be shown. The performance of the Tsai-Partington test increased in the second task block in comparison with the first task block, but no significant effects of exposure time were observed for any other task. No significant interaction between thermal condition and exposure time was observed. Combining the performance index (*PI*) of all tasks, cognitive performance decreased by 10% at T26 and by 6% at T28, in comparison with T24.

$$\mathrm{z}\left(PI_{i,j}\right) = \frac{PI_{i,j}}{\frac{1}{n}\sum_{j=1}^{n} PI_{i,j}} \qquad (2)$$

where $PI_{x,j}$ is the performance index of a task of subject *i* at thermal condition *j* (T24, T26, or T28).

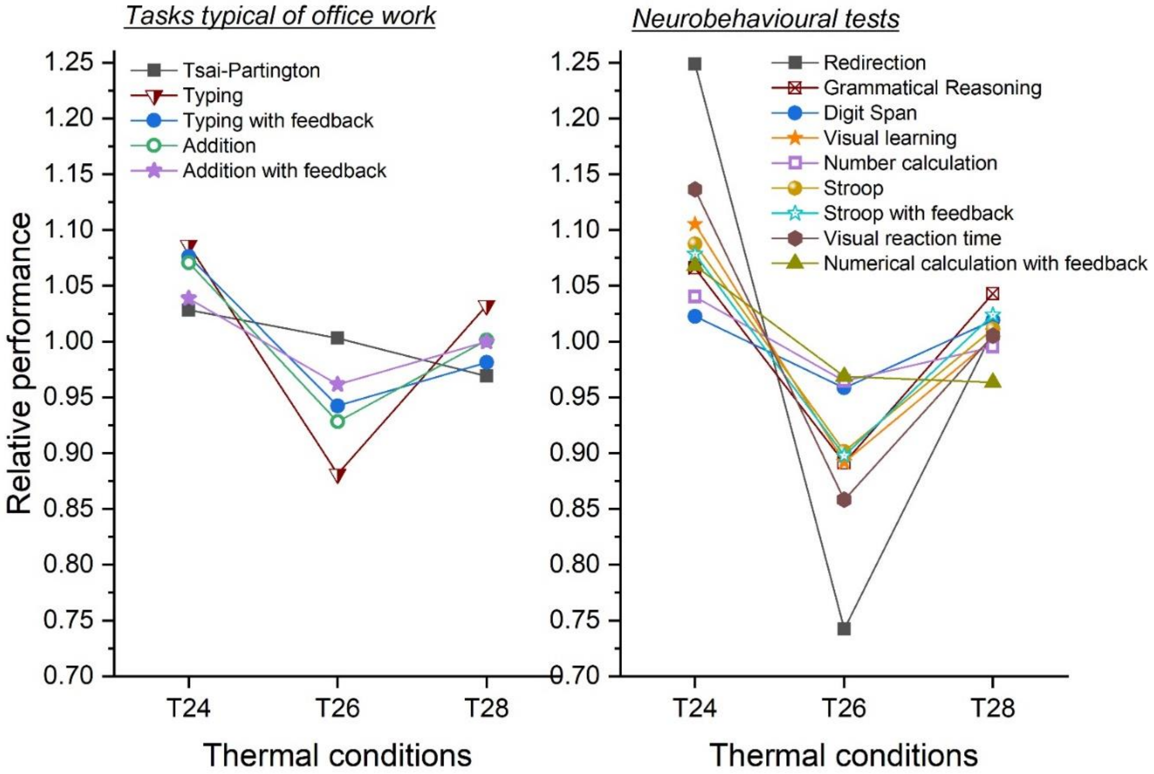

Figure 2 Performance (Z scores) of tasks under the three conditions. Note that clothing and air movement also differed between conditions so the trend should not be interpreted as being due only to differences in air temperature.

Table 5 Performance of tasks under the three conditions; a negative relative change in the performance index indicates that performance decreased at T26 or T28 compared to T24. *P*-values are for a 2-tail test, ***$P<0.001$, **$P<0.01$, *$P<0.05$. f - Cohen's f.

Task	Performance index (Mean±STD)			Change in performance	Thermal effects		Post-hoc LSD analysis
	T24	T26	T28		P	f	
Tsai-Partington	23.6±1.4	23.0±1.2	22.3±2.7	T26: -2.5%; T28: -5.4%	**	0.45	T24-T26**, T24-T28**
Typing	129.6±26.0	112.4±22.8	121.5±26.6	T26: -13.3%; T28: -6.2%	***	0.84	T24-T26***, T26-28***, T24-28**
Typing with feedback	138.0±31.9	127.4±26.5	133.1±31.5	T26: -7.7%; T28: -3.5%	***	0.62	T24-26***, T26-28**, T24-28*
Addition	9.65±0.21	9.50±0.31	9.54±0.36	T26: -1.6%; T28: -1.2%	***	0.96	T24-26***, T26-28***, T24-28*
Addition with feedback	9.52±0.25	9.48±0.39	9.45±0.24	T26: -0.4%; T28: -0.7%	***	0.58	T24-26***, T24-28***
Redirection	0.82±0.19	0.48±0.12	0.67±0.18	T26: -40.9%; T28: -18.9%	***	1.41	T24-26***, T26-28***, T24-28***
Grammatical Reasoning	0.16±0.04	0.14±0.07	0.16±0.05	T26: -12.6%; T28: -0.7%	0.13	0.26	/
Digit Span	10.49±1.56	9.81±1.27	10.46±1.79	T26: -6.5%; T28: -0.3%	0.09	0.27	/
Visual learning	0.83±0.23	0.68±0.25	0.75±0.20	T26: -18.2%; T28: -9.9%	***	0.50	T24-26***, T24-28**
Number calculation	0.48±0.07	0.44±0.07	0.46±0.06	T26: -7.5%; T28: -4.3%	**	0.44	T24-26**, T24-28**
Numerical calculation with feedback	0.50±0.08	0.45±0.08	0.45±0.09	T26: -9.3%; T28: -9.3%	**	0.45	T24-26**, T24-28**
Stroop	0.48±0.10	0.39±0.07	0.45±0.09	T26: -17.8%; T28: -7.1%	***	0.86	T24-26***, T26-28***, T24-28**
Stroop with feedback	0.50±0.10	0.41±0.09	0.47±0.10	T26: -17.1%; T28: -5.0%	***	0.76	T24-26***, T26-28***, T24-28**
Visual reaction time	1.52±0.43	1.14±0.30	1.34±0.31	T26: -25.2%; T28: -12.0%	***	0.71	T24-26***, T26-28**, T24-28***

3.3 Physiological responses

3.3.1 Skin temperature

Figure 3 shows the variation of forehead skin temperature throughout each exposure; it took about 40 min to reach a stable forehead skin temperature at T24 and only about 10min at T26 and T28. The skin temperature values averaged across the whole exposure differed significantly between conditions (*P*<0.001, *f*=0.74); paired comparisons show that the average forehead skin temperature was lower at T24 than at T26 or T28 (*P*<0.001), while no significant difference was observed between T26 and T28.

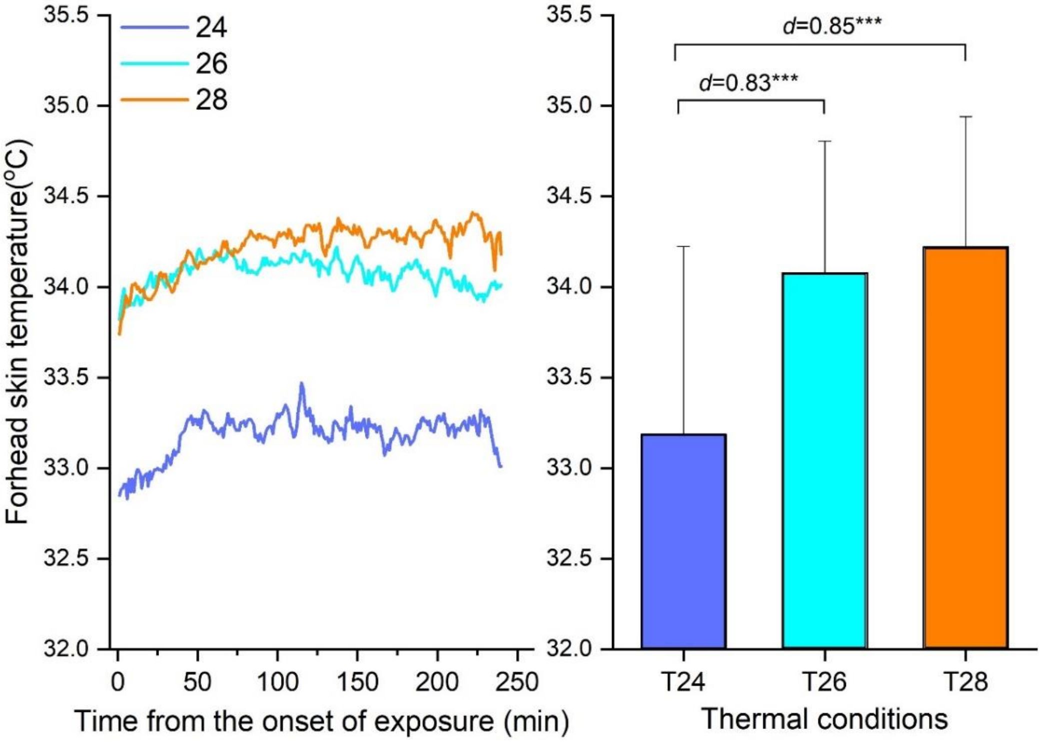

Figure 3 Variation of forehead skin temperature with time (left) and average forehead skin temperature across the whole exposure (right) at the three temperature conditions (*d*- Cohen's d, ****P*<0.001).

3.3.2 Heart rate and heart rate variability (HRV)

The results for heart rate and PNN50 are shown in Figure 4. The averaged heart rate (*P*=0.004, *f*=0.42) and PNN50 (*P*=0.001, *f*=0.46) differed significantly between the three thermal conditions, but no significant differences in LF/HF between conditions were observed (*P*=0.19, *f*=0.22). The mean values of LF/HF were 1.04±0.23, 1.07±0.25, 1.09±0.22, respectively at T24, T26 and T28. Compared with T24, heart rate increased significantly and PNN50 decreased significantly at T26 and T28 (*P*<0.01).

3.3.3 Oxygen saturation (SpO2)

Figure 5 shows the SpO2 values measured at the beginning and end of exposure to the three conditions. At the beginning of an exposure (from 0 min to 8 min), no significant difference in SpO2 was observed between the thermal conditions (*P*=0.55, *f*=0.13). Towards the end of an exposure, i.e., after Task Block 2 (from 232 min to 240 min), SpO2 differed significantly between the thermal conditions (*P*=0.006, *f*=0.39): compared with T24, SpO2 was significantly lower at T26 (*P*<0.01) and slightly but not significantly lower at T28. The effect of exposure time on SpO2 was significant (*P*=0.007, *f*=0.49), and the interaction between thermal condition and exposure time was significant (*P*=0.029, *f*=0.33): SpO2 was significantly higher after Task Block 2 than at the beginning of an exposure, but only at T24. No other significant differences were observed.

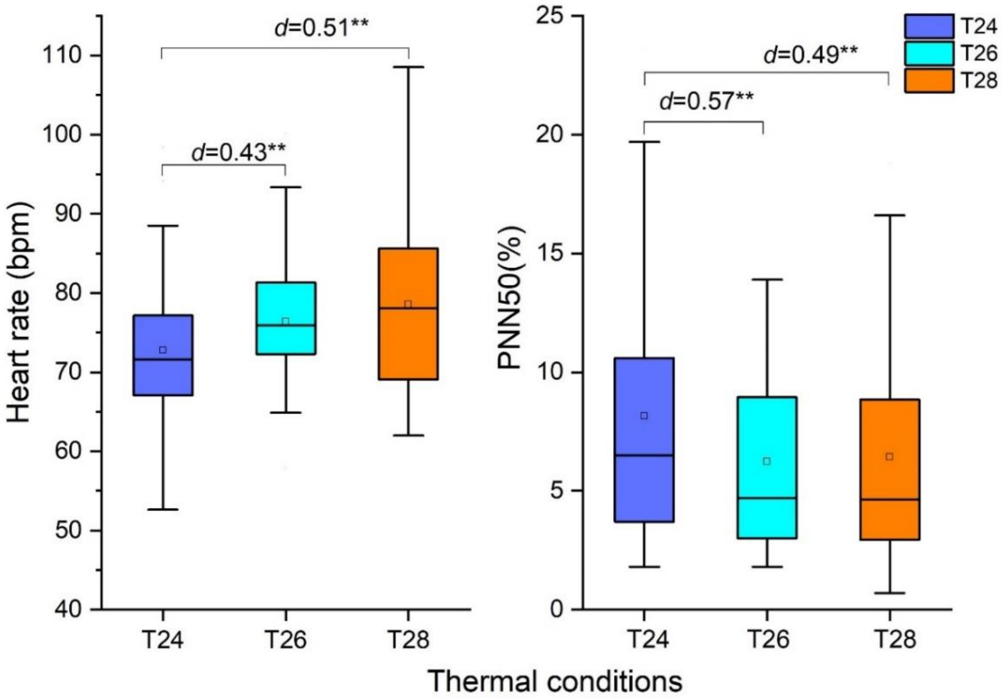

Figure 4 Heart rate and PNN50 at three temperature conditions (*d*-Cohen's d, ***P*<0.01).

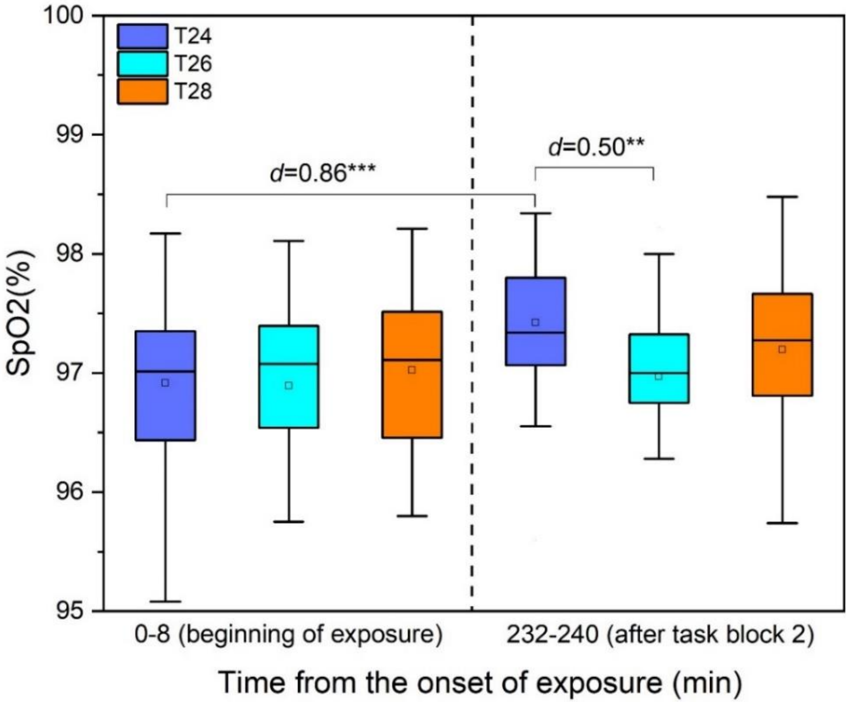

Figure 5 Oxygen saturation (SpO2) measured under the three temperature conditions (*d*-Cohen's d,

**P<0.01).

3.3.4 Salivary alpha-amylase (sAA)

No significant differences between the thermal conditions in sAA were observed for any of the three sampling occasions (upon entering, P=0.59, f=0.12; 25 min after entering, P=0.44, f=0.15; 232 min after entering, P=0.25, f=0.20). Neither exposure time (P=0.53, f=0.14) nor the interaction of thermal condition with exposure time (P=0.21, f=0.21) reached significance (see Supplementary Material, Table S1).

3.4 Subjective ratings

3.4.1Thermal comfort

Of the five assessments, the effect of thermal condition on thermal sensation votes (TSV) was significant at each assessment (P<0.001, see Supplementary Material, Table S2). Mean TSV was higher at higher air temperatures although the majority of the thermal sensation votes remained within the range -0.5 to 0.5 (Table S2). They felt cooler at T24 (Mean TSV was between -0.32±0.36 and 0.02±0.13), neutral at T26 (0.01±0.12 and 0.19±0.40), and slightly warmer at T28 (TSV between 0.03±0.11 and 0.51±0.34), as can be seen in the Supplementary Material (Table S2). Figure 6 shows pairwise comparisons of TSV between the thermal conditions; during the first half of the exposure (before the break), significant differences between conditions were observed in all of the pairwise comparisons, while during the second half of the exposure, the difference in TSV between T26 and T28 was not significant, although both differed significantly from T24. Longer exposure resulted in cooler thermal sensation (P<0.001, f=0.88), as would be expected if metabolic heat production decreased over time as subjects became fatigued, or if sweating increased over time. The correlation between TSV and forehead skin temperature averaged throughout the exposure is shown in Figure 7. TSV was significantly correlated with forehead skin temperature: the subjects felt warmer when their forehead skin temperature was higher.

Significant differences between the three thermal conditions in thermal comfort votes (TCV) and the acceptability of the thermal environment were observed throughout the exposures, although the subjects indicated that all three conditions were both thermally comfortable and acceptable (see Supplementary Material, Table S2). Figure 8 shows pairwise comparison of TCV between conditions during the exposures. The subjects perceived the environment to be more comfortable at T26 (TCV between 0.39±0.47 and 0.58±0.48) than at T24 (TCV between 0.02±0.26 and 0.30±0.29) or at T28 (TCV between 0.06±0.24 and 0.21±0.34), and only at 30 min exposure did they report being less comfortable at T28 than at T24 (P<0.05) and T26 (P<0.05). They systematically assessed the thermal environment to be more acceptable at T26 (acceptability between 0.50±0.42 and 0.66±0.44) than at T24 (acceptability between 0.05±0.23 and 0.29±0.33) and T28 (acceptability between 0.11±0.30 and 0.24±0.38). The effect of exposure time on thermal comfort did not reach significance (*P*=0.07, *f*=0.26), but its effect on the acceptability of the thermal environment was significant (*P*<0.01, *f*=0.40): subjects perceived the environment to be more acceptable at the beginning than following the exposures (Table S2).

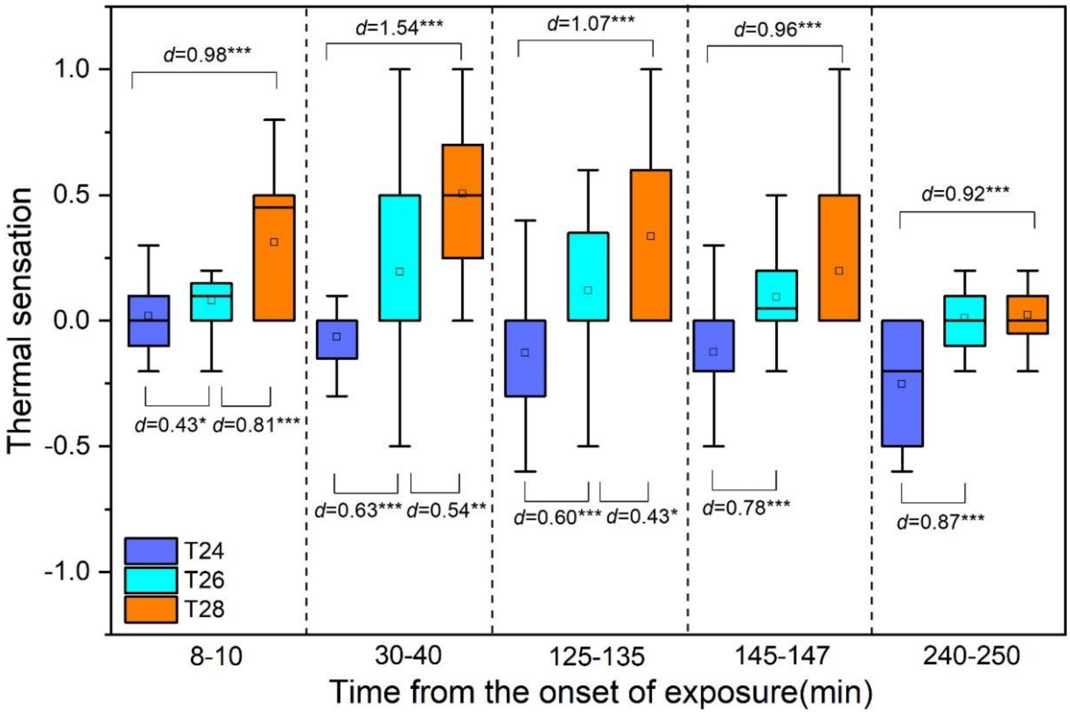

Figure 6 Thermal sensation votes (continuous scale: hot (3), warm (2), slightly warm (1), neutral (0), slightly cool (-1), cool (-2), cold (-3)) at three temperature conditions (*d*- Cohen's d, ****P*<0.001, ***P*<0.01, **P*<0.05)

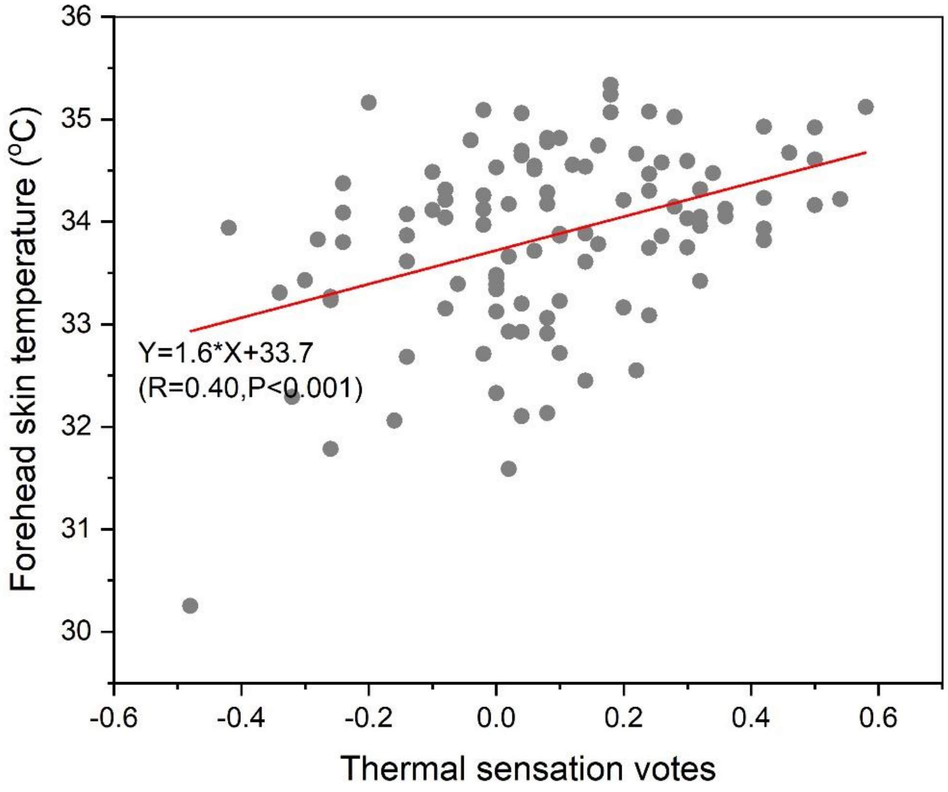

Figure 7 Correlation between thermal sensation votes and forehead skin temperature.

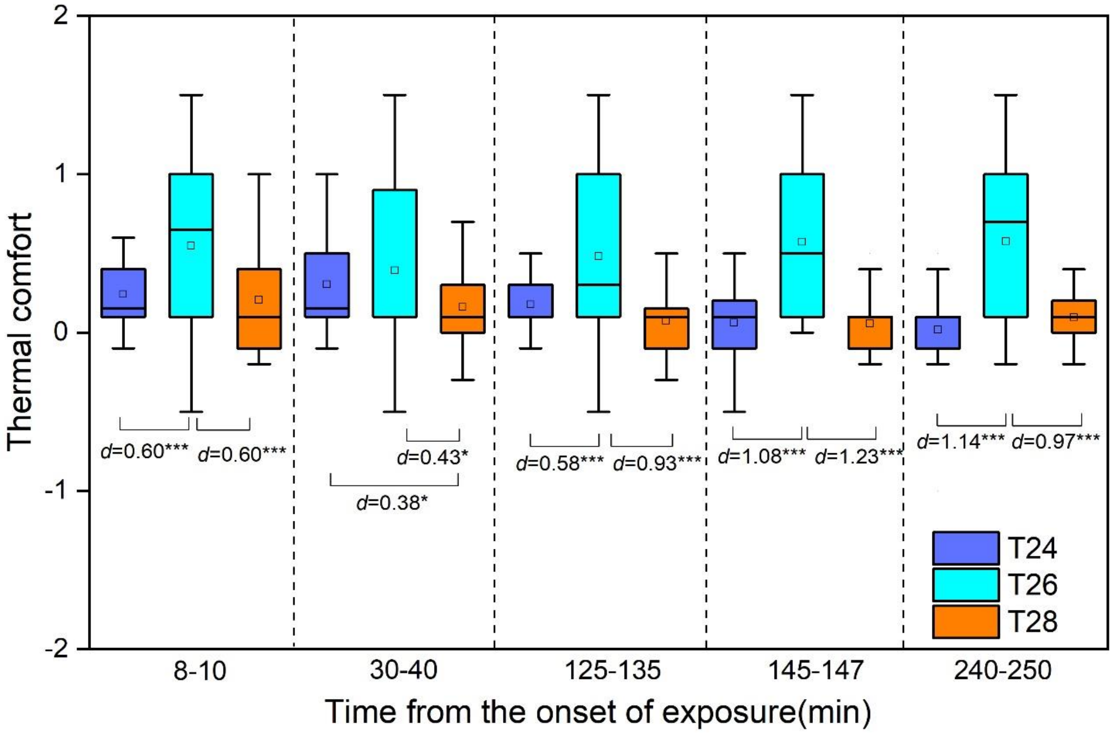

Figure 8 Thermal comfort votes (continuous scale: very comfortable (2); comfortable (1); just comfortable (0.1); just uncomfortable (-0.1); uncomfortable (-1); very uncomfortable (-2)) in the three temperature conditions (d- Cohen's d, ****P*<0.001, ***P*<0.01, **P*<0.05)

3.4.2 Perceived air quality

No significant effects of thermal condition on perceived air quality (PAQ) were observed except at 125-135 min exposure when the subjects had finished Task Block 1 (*P*=0.017, *f*=0.36, see Supplementary Material, Table S3): at this point the subjects perceived the air quality to be significantly less acceptable at T26 than at T24 (*P*<0.01, *d*=0.56). The percentage dissatisfied with air quality was always less than 20%, indicating that the air quality was acceptable under all three conditions (Table S3). PAQ thus varied significantly over time (P=0.007, f=0.36): the subjects perceived the air quality to be less acceptable at 125-135 min exposure, when they had finished Task Block 1 (Table S3).

The perceived odour intensity was consistently low but differed significantly between the three conditions throughout the exposure (Table S3). Figure 9 shows pairwise comparisons of odour intensity at five points in time during the exposure. The perceived odour intensity was significantly higher at T26 than at T24 on all 5 occasions, and on the last two occasions (after 145 min of exposure) it was also significantly higher at T26 than at T28.

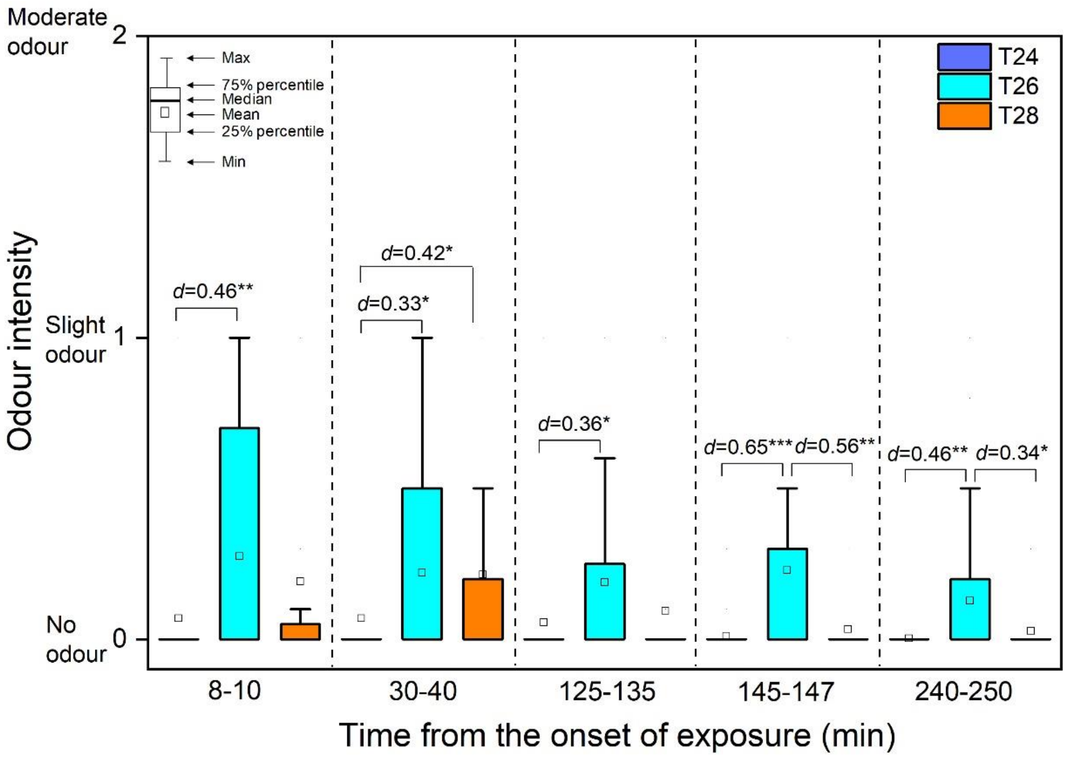

Figure 9. Ratings of odour intensity (continuous scale: no odour-0, slight odour-1, moderate odour-2, strong odour-3, very strong odour-4, overwhelming-5) under the three temperature conditions (*d*- Cohen's d, ***P<0.001, ** P<0.01, * P<0.05).

3.4.3 Sweating assessments

Significant differences between conditions in subjective assessments of sweating were observed at the end of Task Block 1 (*P*=0.007, *f*=0.41) and Task Block 2 (*P*=0.016, *f*=0.36), when subjective assessments of sweating were significantly higher at T28 than at T24 (*P*<0.01). The effects of exposure time on these assessments did not reach significance (*P*=0.66, *f*=0.08). Figure 10 shows subjective assessments of sweating at the three conditions: most subjects reported no sweating at T24 and more subjects felt that their skin was sticky at higher temperatures.

3.4.4 Intensity of subclinical health symptoms

Significant differences between conditions in the intensity of most acute subclinical health symptoms were observed. The subjects reported a higher intensity of most symptoms at T26 than at T24 or T28, and a higher intensity of some symptoms at T28 than at T24 (see Supplementary Material, Table S4).

No significant differences between the thermal conditions and no effects of exposure time could be shown on sleepiness assessments (SLP), self-estimated work performance or willingness to perform work (see Supplementary Material, Table S5).

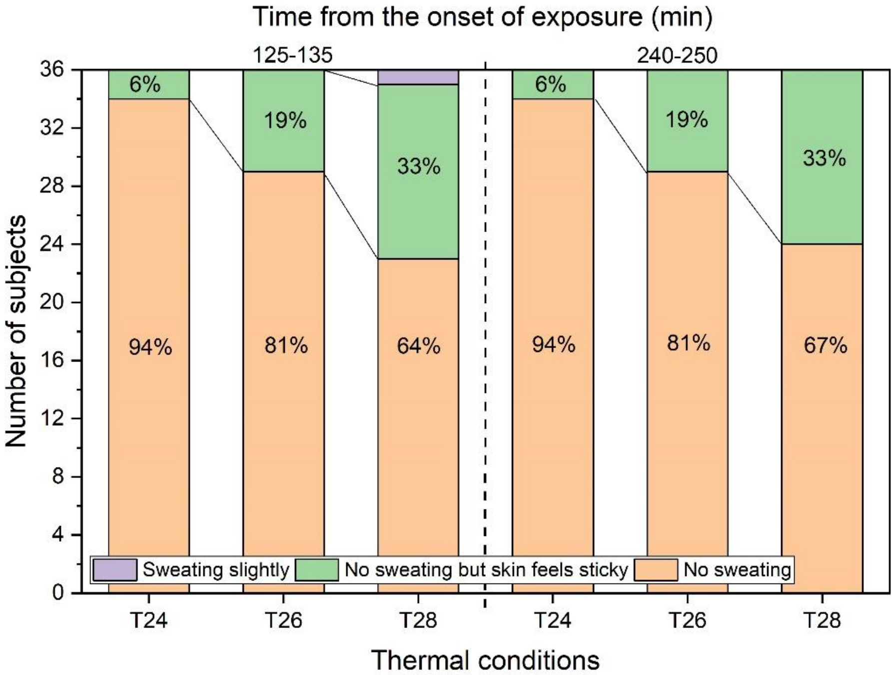

Figure 10 Subjective ratings on sweating (5-point scale: no sweating-0, no sweating but skin feels sticky -1, sweating slightly -2, sweating-3, sweating freely-4) at three temperature conditions

3.4.5 Subjective workload (NASA-TLX)

Significant differences between conditions in overall workload assessment were observed during Task Block 1 ($P<0.001$, $f=0.70$) and Task Block 2 ($P=0.044$, $f=0.31$) and longer exposure resulted in higher overall workload ratings ($P<0.001$, $f=0.58$). Subjects consistently rated mental demand, temporal demand, stress and overall workload significantly higher at T26 than at T24 or T28 (Table S6).

4. Discussion

The most important finding of the present study is that, within the thermally comfortable range ($-0.5<TSV<+0.5$), elevated air temperatures (26°C and 28°C) resulted in poorer cognitive performance when compared to a lower temperature of 24°C (Figure 2, Table 5). This is consistent with the results of our previous study, in which cognitive performance was significantly lower at 27°C than at 23°C even though the subjects were able to remain thermally comfortable at both temperatures by adjusting their clothing [13]. The present study was carried out in summer and the subjects were Chinese living in a region with hot humid summers, while our previous study was carried out in the heating season and the subjects were Caucasians living in a temperate climate in Northern Europe. Taken together, these two studies provide strong justification for generalizing the conclusion that temperatures at the lower end of the thermal comfort range are more beneficial for cognitive performance. This is in accordance with two published dose-response relationships between temperature and performance, based on reviews of the world literature

[11, 12], both of which indicate that a comfortably cool environment is optimal for cognitive performance.

A striking aspect of the present results is that cognitive performance was so clearly affected “across the board”, i.e., significant negative effects of elevated temperatures could be shown on all but one of the 14 metrics of cognitive performance in Table 5, within the range of thermal comfort. It is much more common in such experiments that thermal effects on many of the selected metrics fail by chance to reach significance, giving the impression that only certain types of cognition are affected, as in our previous experiment [13], in which data from only 11 subjects was available. The present results, using data from 36 subjects, provide evidence that this would be a mistaken conclusion and that elevated temperatures have negative effects on most types of cognition. The present study was performed in an air conditioned (AC) room, which does not prove that such effects would occur in naturally ventilated rooms. However, in an observation study of 44 young adults, cognitive performance was lower in the non-AC group (indoor temperature: mean=26.3°C, SD=2.5°C) compared with the AC group (indoor temperature: mean=21.4°C, SD=1.9°C) [8]. This suggests that cognitive function deficits resulting from moderately raised indoor temperatures would also be observed in naturally ventilated rooms.

In considering causation, it has been suggested that under periods of cognitive demand a number of physiological responses are brought into play and serve to increase the delivery of metabolic substrates to active neural tissue [25]. The physiological responses observed in the present study suggest two possible mechanisms by which cognitive performance was decreased by elevated air temperatures: a higher pNN50 (Figure 4) and increased oxygen saturation SPO2 (Figure 5) were both associated with increased cognitive performance at T24. pNN50 is closely correlated with PNS activity, higher pNN50 indicating higher PNS activity [21]. Compared with 26°C, the increased pNN50 at 24°C indicates that in that condition the subjects had higher PNS activity, lower stress, and increased cognitive capacity [22,23]. Previous studies have reported higher pNN50 values in thermal environments in which work performance improved [13, 33]. SpO2 is an estimate of the arterial blood oxygen saturation level and indicates the percentage of haemoglobin molecules in the arterial blood that are saturated with oxygen. Previous studies have shown that the brain increases its uptake of oxygen into active brain areas during cognitively demanding tasks [25, 34], and higher oxygen saturation is associated with improved cognitive performance [25, 26]. Figure 5 shows that SpO2 was higher at T28 than at T26, and although this difference did not reach significance it is compatible with the observation that the performance of many tasks was better at T28 than at T26, possibly because the stimulating effect of increased air movement caused subjects to exert more effort, which overcompensated for the 2°K increase in air temperature between T26 and T28 while failing to compensate for the 4°K difference between T24 and T28. In previous studies, higher SpO2 was also associated with higher cognitive performance at lower temperatures (22°C, 23°C) than at elevated temperatures (30°C, 27°C) [3, 13]. These results suggest that even when physiological responses at higher temperatures are mild and have no clinical importance, they may be sufficient to produce negative effects on performance. Brain wave measurements also provide evidence that a comfortably cool environment is beneficial for cognitive performance. Yao et al. reported that alpha frequencies were dominant in EEG recorded from subjects in a slightly cool environment [24]. This is believed to indicate internalized attention and a state of relaxed alertness that is conducive to mental health [35].

The differences in air temperature were clearly perceived by the subjects (Figure 6, Table S2) even though thermal comfort had been maintained by adjusting clothing and by increasing air movement at the highest temperature: Figure 8 and Table S2 show that thermal comfort as indicated by TCV was slightly but significantly higher at T26 than at T24 or T28. Figure 2 and Table 5 show that the performance of many tasks was worse at T26 than at T24 or T28, so even within the thermal comfort range increasing thermal comfort may have made subjects disinclined to exert effort to counteract thermal effects on cognitive performance. Forehead skin temperature increased at the higher temperatures (Figure 3) and was significantly correlated with thermal sensation votes (Figure 7), suggesting there is an intrinsic relationship between temperature perception and skin temperature. Our nervous system continuously evaluates environmental temperatures and controls thermoregulatory effectors appropriately by parallel but distinct effector-specific neural pathways, depending on whether signals are sent by warm or cold cutaneous thermal receptors [36]. Warm receptors are activated by heat and cold receptors are activated by cold. Transient receptor potential (TRP) channels that transduce cutaneous cold and warm stimuli have been identified [36]. A warm receptor, TRPV4 near the surface of the epidermis is activated by warm stimuli with a threshold of 25-34°C. It has a lower threshold than other warm receptors [36]. It seems likely that this warm receptor was activated at T26 and T28 but not at T24 in the present experiment. The signals from this warm receptor may activate thermoregulatory effectors, for example by dilating cutaneous blood vessels to increase heat loss, as indicated by the higher forehead skin temperatures measured at T26 and T28 than at T24. These thermoregulation activities may be the primary cause for the differences in cognitive performance, physiological responses and acute subclinical health symptoms between the three temperatures. Humans may accept a wide range of thermal conditions, but cognitive performance does not appear to be guaranteed by the attainment of thermal comfort. It would be wrong to assume that there are no negative effects on cognitive performance when thermal comfort is maintained at higher temperatures and that psychological acceptance will overcome negative effects. The air temperature at which thermal comfort is achieved should also be taken into account in defining thermal conditions that are optimal for cognitive function. Neuroscientific research is required to identify the causative mechanism for these effects.

In our previous directly comparable experiment [13], the intensity of acute subclinical health symptoms did not differ significantly between the two air temperatures (23 and 27°C) at which subjects were able to maintain thermal comfort by adjusting clothing insulation, while they differed significantly between conditions in the present exposures in the 24-28°C range. The absence of significance in the first experiment may simply be due to the much lower number of subjects (11 instead of 36 in the present experiment) but if the difference is genuine, it may have occurred because RH was markedly higher (59-66% in the present experiment, instead of 38-42% in the first experiment).

In the present experiment, gentle air movement from a ceiling fan reduced the negative effects of elevated air temperature on acute subclinical health symptoms and on the performance of some cognitive tests. This is consistent with reports of improved cognitive performance with personalized ventilation (local air flow) at high room temperature and humidity [16]. In other published experiments, air movement was not unexpectedly assessed positively in a warm environment and occupants would have preferred more air movement rather than less even when reporting a ‘neutral’ thermal sensation [14]. In the present experiment, air movement must have increased convective and evaporative heat transfer from human body to the environment, as we can see that no significant difference in forehead skin temperature or sweating assessment was observed between T26 and T28, yet the subjects maintained thermal comfort at T28. Increasing air movement resulted in other positive effects besides increased heat loss: subjective ratings of odour intensity, SBS symptom intensity and workload were consistently lower at T28 (with more air movement) than they were at T26, in which condition there was very little air movement. These results suggest that the indoor air was perceived as less stuffy when there was more air movement, and this positive impression may have led to an increase in the effort exerted to counteract thermal effects on cognitive performance. More studies are needed to confirm that this was the mechanism by which the addition of gentle air movement was able to partially restore cognitive performance within the thermal comfort range. However, it should be remembered that cognitive performance at T28 was still significantly worse than at T24, even with added air movement at T28.

No effect of room temperature on the level of salivary alpha-amylase (sAA) in saliva was observed (Table S1). Similar results were observed in previous studies [3, 13, 37, 38], which consistently showed that alpha-amylase levels did not change at moderately elevated temperatures compared with a neutral temperature. Since the secretion of sAA is activated by the sympathetic nervous system [27], these results suggest that the activity of the sympathetic nervous system was not intensified at these moderately elevated temperatures. However, alpha-amylase levels have been shown to be affected by low temperatures [38].

Comparing the results on cognitive performance, physiological responses and subjective ratings, it is worth noting that cognitive performance was much more sensitive to changes in thermal conditions than were physiological responses or subjective ratings of comfort. Cognitive functions are mediated by the central nervous system, which has been reported to be particularly vulnerable to environmental disturbance [39]. Changes in cognitive performance can thus be used with advantage to evaluate the early and less obvious effects of environmental factors.

5. Conclusions

Thermal comfort was achieved at an air temperature of 24°C with a clothing insulation of 0.7 clo (T24), at 26°C with 0.5 clo (T26), and at 28°C with 0.5 clo and a ceiling fan in operation (T28). Even within this thermally comfortable range, a cooler environment resulted in improved cognitive performance: compared with T24, cognitive performance decreased by 10% at T26 and by 6% at T28. At the elevated air temperatures, lower PNN50 and SpO2 values indicate that the subjects experienced lower activity of the parasympathetic nervous system and a lower arterial blood oxygen saturation level, changes that are both associated with poorer cognitive performance. The intensity of acute subclinical health symptoms and subjective workload increased at the elevated temperatures. These results all suggest that where cognitive performance is a priority, it is wise to ensure a comfortably cool environment.

Some (but not all) of the negative effects of elevated air temperature on cognitive performance were mitigated by supplying increased air movement by operating a ceiling fan. Subjects rated the intensity of their acute subclinical health symptoms and their subjective workload as lower, and performed some cognitive tests better, at T28 than at T26, although T28 was still worse than T24 in all of these respects. These results show that in a warm environment, air movement is beneficial not only for thermal comfort, but also for cognitive performance. This new evidence should encourage designers to use fans or natural ventilation to reduce the need for mechanical cooling.

The results of the present study indicate that cognitive performance is much more sensitive to changes in the thermal environment than are subjective comfort ratings or physiological responses, at least within the thermally comfortable range, so for learning and office work, cognitive performance must be considered as the key criterion. The fact that self-estimated performance did not differ significantly between conditions, even though average measured performance differed by up to 10%, shows that the subjects were not themselves aware that they were working less well under the two warmer conditions.

6. Acknowledgements

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Table S1. Alpha-amylase activity in saliva (IU/L) under the three thermal conditions (mean ± standard deviation)

Time (min)	Upon entering (0-8 min)	25 min after entering (Block 1)	232 min after entering (Block 2)
T24	1204±233	1203±251	1249±264
T26	1196±275	1277±287	1185±249
T28	1243±229	1235±214	1163±193
2-tail *P*-value	0.59	0.44	0.25
Cohen's *f*	0.12	0.15	0.20

Table S2. Subjective assessments of thermal sensation, thermal comfort and acceptability of the thermal environment under the three thermal conditions (mean ± standard deviation)

Time from the onset of exposure (min)	8-10	30-40	125-135	145-147	240-250
Thermal sensation (hot (3); warm (2); slightly warm (1); neutral (0); slightly cool (-1); cool (-2); cold (-3))					
T24	0.02±0.13	-0.06±0.11	-0.13±0.24	-0.13±0.21	-0.32±0.36
T26	0.08±0.09	0.19±0.40	0.12±0.27	0.09±0.15	0.01±0.12
T28	0.31±0.27	0.51±0.34	0.34±0.41	0.20±0.27	0.03±0.11
2-tail *P*-value	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Cohen's *f*	0.88	0.89	0.73	0.75	0.90

Thermal comfort (very comfortable (2); comfortable (1); just comfortable (0.1); just uncomfortable (-0.1); uncomfortable (-1); very uncomfortable (-2))					
T24	0.24±0.19	0.30±0.29	0.18±0.19	0.06±0.22	0.02±0.26
T26	0.55±0.48	0.39±0.47	0.48±0.45	0.57±0.40	0.58±0.48
T28	0.21±0.34	0.15±0.26	0.08±0.24	0.06±0.24	0.10±0.19
2-tail *P*-value	$<0.001^{***}$	$<0.05^{*}$	$<0.001^{***}$	$<0.001^{***}$	$<0.001^{***}$
Cohen's *f*	0.54	0.35	0.70	0.99	0.99
Acceptability of thermal environment (clearly acceptable (1); clearly unacceptable (-1))					
T24	0.29±0.33	0.23±0.21	0.19±0.19	0.14±0.19	0.05±0.23
T26	0.66±0.44	0.58±0.45	0.50±0.42	0.61±0.37	0.50±0.42
T28	0.24±0.38	0.11±0.30	0.20±0.43	0.13±0.25	0.16±0.28
2-tail *P*-value	$<0.001^{***}$	$<0.001^{***}$	$<0.001^{***}$	$<0.001^{***}$	$<0.001^{***}$
Cohen's *f*	0.63	0.75	0.51	1.04	0.71

$^{***}P<0.001$, $^{**}P<0.01$ and $^{*}P<0.05$ indicate significant differences between conditions.

Table S3. Perceived air quality and odour intensity under the three thermal conditions (mean ± standard deviation)

Time from the onset of exposure (min)	8-10	30-40	125-135	145-147	240-250
Acceptability of air quality (clearly acceptable (1); clearly unacceptable (-1))					
T24	0.40±0.24	0.34±0.27	0.33±0.20	0.30±0.21	0.41±0.21
T26	0.43±0.34	0.39±0.34	0.22±0.20	0.32±0.19	0.43±0.24
T28	0.36±0.29	0.35±0.39	0.28±0.22	0.30±0.22	0.41±0.23
2-tail *P*-value	0.45	0.69	<0.05*	0.64	0.60
Cohen's *f*	0.15	0.10	0.36	0.11	0.11
% dissatisfied with air quality (Gunnarsen and Fanger, 1992)					
T24	9	12	13	15	9
T26	8	9	21	13	8
T28	11	12	16	14	9
Odour intensity (no odour (0), slight odour (1), moderate odour (2), strong odour (3), very strong odour (4), overwhelming (5))					
T24	0.07±0.24	0.07±0.24	0.06±0.23	0.01±0.05	0.00±0.02
T26	0.28±0.43	0.22±0.37	0.19±0.34	0.23±0.35	0.13±0.27
T28	0.19±0.38	0.21±0.38	0.09±0.25	0.03±0.10	0.03±0.10
2-tail *P*-value	<0.05*	<0.05*	<0.05*	<0.001***	<0.01**
Cohen's *f*	0.31	0.27	0.26	0.59	0.40

** *P*<0.01 and * *P*<0.05 indicate significant differences between conditions observed.

Table S4. Perceived intensity of acute subclinical health symptoms under the three thermal conditions (mean ± standard deviation)

Symptoms	**Time† (min)**	**Conditions**			**Condition effects**		**Post-hoc LSD analysis**
		T24	**T26**	**T28**	**2-tail *P*-value**	**Cohen's *f***	
Nose dry (0)	30-40	82±11	70±15	79±12	***	0.64	T24-T26***;T26-T28***
Nose running (100)	125-135	81±8	70±17	75±12	***	0.54	T24-T26***;T24-T28**
	240-250	78±9	72±14	76±7	*	0.31	T24-T26*
Throat dry (0)	30-40	76±11	58±23	75±16	***	0.68	T24-T26***;T26-T28***
Throat not dry (100)	125-135	73±11	54±25	68±13	***	0.70	T24-T26***;T24-T28**;T26-T28***
	240-250	26±10	47±22	30±8	***	0.82	T24-T26***;T24-T28*;T26-T28***
Mouth dry (0)	30-40	76±11	58±19	73±17	***	0.66	T24-T26***;T26-T28***
Mouth not dry (100)	125-135	70±16	57±21	64±14	**	0.47	T24-T26**; T24-T28*;T26-28*
	240-250	68±14	56±19	65±15	**	0.45	T24-T26**;T26-T28**
Lips dry (0)	30-40	70±16	54±18	70±18	***	0.63	T24-T26***;T26-T28***
Lips not dry (100)	125-135	65±17	47±19	63±16	***	0.66	T24-T26***;T26-T28***
	240-250	65±13	52±18	64±16	***	0.54	T24-T26***;T26-T28***
Skin dry (0)	30-40	80±8	65±19	80±6	***	0.72	T24-T26***;T26-T28***
Skin not dry (100)	125-135	76±8	65±21	75±9	**	0.51	T24-T26**;T26-T28**
	240-250	77±10	60±17	77±9	***	0.85	T24-T26***;T26-T28***
Eyes dry (0)	30-40	82±10	71±16	78±10	***	0.50	T24-T26***;T26-T28*
Eyes not dry (100)	125-135	73±13	57±20	73±12	***	0.69	T24-T26***;T26-T28***
	240-250	72±13	62±18	72±9	**	0.43	T24-T26**;T26-T28**
Eyes aching (0)	30-40	87±11	80±17	87±7	**	0.37	T24-T26*;T26-T28*

Eyes not aching (100)	125-135	77±14	67±22	80±13	***	0.53	T24-T26**;T26-T28***
	240-250	80±12	70±20	78±11	**	0.41	T24-T26**;T26-T28*
Severe headache (0)	30-40	92±9	95±7	94±7	0.13	0.25	/
No headache (100)	125-135	88±9	79±17	84±15	*	0.36	T24-T26**
	240-250	84±12	80±18	81±15	0.53	0.14	/
Difficult to think (0)	30-40	85±9	88±9	86±10	0.28	0.19	/
Head clear (100)	125-135	78±10	69±15	75±12	**	0.40	T24-26**;T26-T28
	240-250	79±11	76±15	79±7	0.23	0.21	/
Dizzy (0)	30-40	87±11	88±14	88±13	0.70	0.10	/
Not dizzy (100)	125-135	83±11	74±17	84±8	***	0.49	T24-T26**;T26-T28***
	240-250	79±11	80±16	82±10	0.61	0.11	/
Feeling bad(0)	30-40	83±7	80±13	83±10	0.32	0.18	/
Feeling good(100)	125-135	75±10	60±20	73±12	***	0.57	T24-T26***;T26-T28***
	240-250	72±12	74±13	74±12	0.63	0.11	/
Tired (0)	30-40	79±9	75±13	76±12	0.39	0.16	/
Rested (100)	125-135	67±11	54±18	64±14	***	0.53	T24-T26***;T26-T28**
	240-250	63±12	60±13	65±14	0.25	0.20	/
Hard to concentrate (0)	30-40	81±9	78±12	79±10	0.16	0.23	/
Easy to concentrate (100)	125-135	71±12	60±14	65±14	**	0.43	T24-T26***;T24-T28*
	240-250	66±13	63±15	71±10	**	0.38	T24-T28*;T26-T28**
Depressed (0)	30-40	84±10	83±11	86±8	0.49	0.14	/
Positive (100)	125-135	79±12	65±14	73±14	***	0.56	T24-T26***;T24-T28*;T26-T28**

	240-250	77±12	68±12	73±10	**	0.39	T24-T26**;T26-T28*
Alert (0)	30-40	77±10	68±15	73±10	**	0.44	T24-T26**
Sleepy (100)	125-135	65±13	49±19	65±16	***	0.66	T24-T26***;T26-T28***
	240-250	60±16	56±14	63±12	0.08	0.28	/

*** *P*<0.001, ** *P*<0.01 and * *P*<0.05 indicate significant differences between conditions.

†Time from the onset of exposure (min).

Table S5. Sleepiness, self-estimated work performance and willingness to perform work under the three thermal conditions (mean ± standard deviation)

Time from the onset of exposure (min)	**T24**	**T26**	**T28**	**2-tail *P*-value**	**Cohen's *f***
Do you feel alert or sleepy right now? 1-extremely alert, 9-very sleepy					
125-135	5.4±1.3	4.8±1.9	5.1±1.4	0.27	0.20
240-250	5.3±1.4	5.2±1.5	4.6±1.5	0.13	0.25
Right now, I'm able to work: 0-low, 100-high					
125-135	71.9±7.8	73.2±12.5	71.8±8.3	0.71	0.09
240-250	69.2±11.1	67.9±11.6	71.9±7.9	0.09	0.27
Right now, my willingness to perform the work is: 0- low, 100-high					
125-135	62.2±12.7	58.3±18.6	60.1±12.8	0.31	0.18
240-250	58.1±13.4	58.8±16.7	54.9±10.2	0.34	0.18

Table S6. Mental workload (Raw TLX) and the six-component scales of NAS-TLX under the three thermal conditions (mean (standard deviation)). P-values are for a 2-tail test, ***$P<0.001$, **$P<0.01$, *$P<0.05$. f - Cohen's f.

Time from the onset of exposure (min)	**83-85 (task block 1)**						**187-189 (task block 2)**					
	T24	T26	T28	*P*	*f*	Post-hoc	T24	T26	T28	*P*	*f*	Post-hoc
Mental workload (Raw TLX)	47.9	54.1	46.7	<0.001	0.70	T24-T26***	51.7	55.5	51.9	<0.05	0.31	T24-T26**
	(8.0)	(6.5)	(5.8)	***		T28-T26***	(9.0)	(7.6)	(7.3)	*		T28-T26*
Mental demand	61.7	67.4	55.8	<0.001	0.55	T24-T28**	60.4	67.6	60.1	<0.05	0.38	T24-T26**
(A lot-100, A little-0)	(15.0)	(11.6)	(11.3)	***		T26-T28**	(13.9)	(18.1)	(9.1)	*		T28-T26**
Physical demand	32.1	35.3	26.9	0.06	0.29	/	37.6	37.6	36.9	0.97	0.03	/
(A lot-100, A little-0)	(19.3)	(23.7)	(12.1)	NS			(16.3)	(21.2)	(13.3)	NS		
Temporal demand	36.3	53.5	35.8	<0.001	0.75	T24-T26***	41.3	46.8	44.0	0.41	0.16	/
(A lot-100, A little-0)	(13.0)	(15.3)	(13.8)	***		T28-T26***	(15.6)	(19.6)	(19.7)	NS		
Performance	64.2	70.4	69.2	0.17	0.23	/	63.9	72.9	65.6	<0.01	0.46	T24-T26***
(Poor-100, Well-0)	(17.1)	(15.7)	(15.4)	NS			(14.2)	(10.5)	(13.0)	**		T28-T26***
Stress	57.9	65.8	59.4	<0.05	0.37	T24-T26**	62.9	70.8	61.8	<0.001	0.47	T24-T26**
(A lot-100, A little-0)	(14.2)	(14.0)	(14.5)	*		T28-T26*	(14.2)	(12.4)	(12.2)	***		T28-T26***
Frustration level	35.6	32.5	33.2	0.64	0.11	/	43.9	37.5	42.6	0.22	0.21	/
(A lot-100, A little-0)	(13.4)	(18.1)	(15.8)	NS			(14.8)	(17.0)	(18.0)	NS		

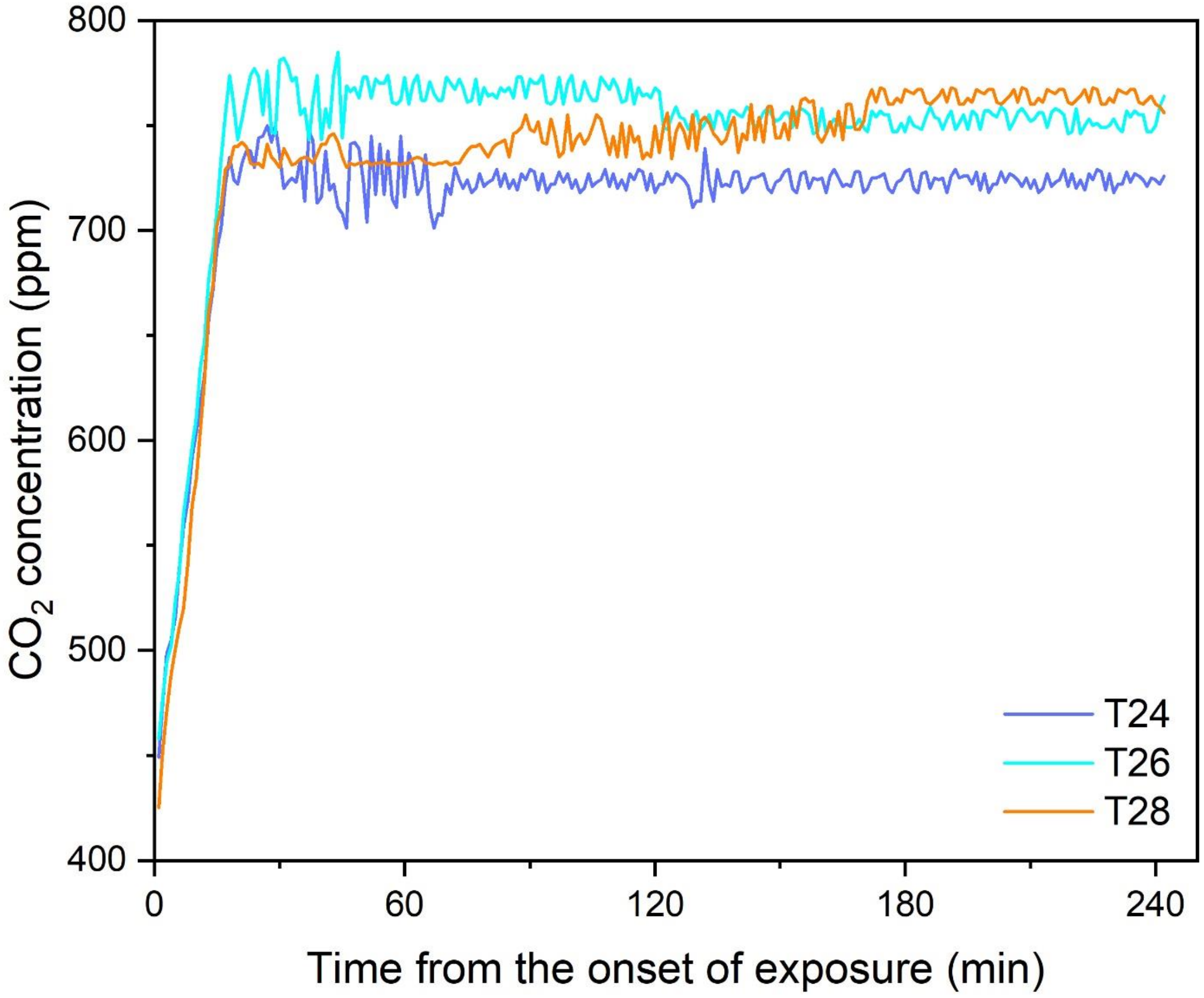

Figure S1 CO_2 concentration during exposure in the room under the three thermal conditions