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Effects of thermal sensation and acclimatization on cognitive performance of adult female students in Saudi Arabia using multivariable-multilevel statistical modeling

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Abstract

In the hot climate of Saudi Arabia, people living year-round in air-conditioned spaces are likely to develop high expectations for homogeneity and cool temperatures, becoming potentially more sensitive if thermal conditions deviate from the comfort zone they expect. This paper presents the results from a field intervention investigating the association between participants' thermal sensations with cognitive performance in a female university in Saudi Arabia. The climatic context plays a key role in choosing Saudi Arabia, whereas the total reliance on air-conditioners (AC) for cooling is believed to have significant effects on occupants' perceptions of the comfort temperature. Results reveal discrepancies in the actual thermal sensations between the Saudi and non-Saudi participants which affected their performances. "Cool" and "Slightly Cool" sensations versus neutral were associated with significant lower percentage of errors and significant higher speed for all participants independently of any association with ethnicity and acclimatization. The estimates remained significant even after adjusting for ethnicity and the number of years spent in the country and the set temperature of AC at home. Implications of the study suggest a preference for staying cool when working independently of acclimatization status.

KEYWORDS
acclimatization, air-conditioned buildings, cognitive performance, educational buildings, hot climates, thermal sensations

1 | INTRODUCTION

The interaction between people and the thermal environment is complex and has been the subject of a number of studies. Numerous adult studies have tried to establish a quantitative relationship between thermal comfort and productivity. Kosonen and Tan[1] illustrated how the productivity loss can be minimized through improved thermal comfort design criteria using a predicted mean votes (PMV) index; however, only the effects of feeling too warm on productivity were reported, and no relationship between PMV and productivity was created. Lan et al.[2] suggested that the optimal range of thermal comfort sensation based on the (PMVs) should be from slightly cool (PMV = −0.5) to neutral (PMV = 0). Regarding the actual thermal sensation votes (TSV), Jensen et al.[3] found that the optimum performance occurred when TSV was −1 (cool). Roelofsen (2001) proposed an optimum range for performance between thermal sensation votes

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of TSV = −0.5 (slightly cool) to TSV = 0.1 (neutral). Most results support that optimum performance is obtained within the comfort zone of TSV between −0.5 and 0.5 (slightly cool and slightly warm). Thames and Willem[4] found that higher mental arousal occurred when lower TSV were obtained. Thermal discomfort was reported to be most likely leading to reduced performance. Some researchers provided evidence that better performance occurred outside the comfort zone due to the arousal effect. In office buildings studies, it was found that thermal discomfort distracts attention and generates complaints and that warmth lowers arousal, exacerbates sick building syndrome (SBS) symptoms and has a negative effect on mental work (e.g., Wargocki and Wyon[5,6]). Seppänen and Fisk[7] found an existing relationship between SBS symptoms and work performance. Wargocki et al.[8] gathered data from 18 studies to construct a relationship between thermal conditions in classrooms and children's performance in school and showed that the performance of psychological tests and school tasks can be expected to increase on average by 20% if classroom temperatures are lowered from 30°C to 20°C and that the temperature for optimal performance is lower than 22°C. However, this relationship is valid only for temperate climates. Scarce data are available on the associations between thermal comfort and performance in hot climates relying on air-conditioners (AC) for cooling and ventilation. Therefore, Saudi Arabia was chosen for this study.

Interestingly, the thermal environment can act as a brain stimulus. It was proven that changes in brain temperature act as a conditioned stimulus which may in return result in behavioral arousal (Kiyatkin[9]). An area in the brain located in the posterior mid cingulate cortex was found to be associated with the hedonic component of temperature sensation, which contrasted with activations generated from skin and core temperatures and has an important cognitive role such as episodic memory retrieval (Spreng[10]). The adaptive thermal comfort theory is related to this context of the effect of the ambient thermal environment not only on the brain, but also on human physiological and psychological responses, as well as behavioral adaptation. In countries such as Saudi Arabia, the potential adaptation to warmer outdoor temperature is counteracted by the pervasive use of air-conditioning, which is likely to heavily affect occupants' expectations of thermal conditions. Furthermore, there is limited variation in insulation values of clothes especially for women due to a highly standardized dress code. Also, the variation in temperatures between seasons is limited, and thus, the effect of AC' acclimatization cannot be neglected in this climatic context. Given the potential interactions with air quality and ventilation rates, this study also evaluated the combined effect of temperature and CO_2 levels (as markers for ventilation rates) on cognitive performance, results are presented in a separate paper, whereas the focus in this paper is on the impact of thermal sensations.

2 | METHODOLOGY

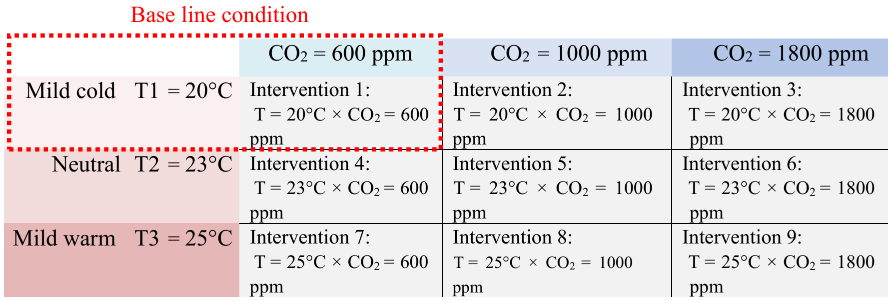
An intervention study was conducted in a selected female university, which represents a typical example of a modern architectural style in Saudi Arabia, students' age 16–23 years. The interventions were performed using a blind cross-over design with repeated measures. Nine exposure conditions were investigated combining temperatures and CO_2 levels, as markers for the ventilation rates, (Table 1) which were the only independent variables while other environmental physical parameters were kept within constant ranges namely: sound levels, lighting intensity, and relative humidity. CO_2 in this study is the bio-effluent from the participants and controlled via ventilation where no other pollutants were monitored, therefore, it cannot be excluded that some of the effects observed at certain CO_2 levels were due to other pollutants.

The study was conducted in three phases: Phase 1: To establish the baseline condition, a brief questionnaire was disseminated to a number of universities and schools in Jeddah—Saudi Arabia—asking about the set AC temperature in classrooms during the academic semesters. Also, sensors (detailed in the physical monitoring section) were inserted in 25 classrooms in the selected case study building. Temperature of 20°C was found to be the most common temperature set in these classrooms and also in 75% of the educational buildings surveyed (338 secondary schools out of the total number of 450 schools approached), and in all of the university buildings surveyed, thus was used as the baseline condition. Due to the limitation of time and resources, CO_2 levels (as markers for ventilation rates) were not collected at this stage, nevertheless, CO_2 levels of 1000 ppm (ventilation: 7.5–8 l/s-p) were included in the exposure conditions of the interventions as it represents the reference according to the existing guidelines for acceptable IAQ defined by the ASHRAE standards (ASHRAE[11]). In addition, CO_2 levels of 600 ppm (ventilation: 20 l/s-p) and 2000 ppm (ventilation: 2.5–3 l/s-p) were included in the exposure conditions since a number of studies have referred to the significant impairment of decision-making skills and cognitive performance at elevated CO_2 levels compared with 600 ppm. Phase 2: a pilot study was conducted in the case study building to examine the feasibility of adopting the proposed methodological approach. It was found that the maximum CO_2 levels that could be reached were 1800 ppm not 2000 ppm. Phase 3: Accordingly, a full intervention study was conducted in two identical classrooms in the selected building, which lasted for 12 months

Practical Implications

This study confirms that there is a strong association between indoor temperature, thermal sensations, and cognitive performance in young adult female students. The practical implications of this research highlight that findings from previous studies may not be applicable to climates such as Saudi Arabia, where the pervasive presence of air-conditioning is not only affecting occupants' preferences for cooler temperatures, but may also impact on their cognitive performance at lower temperatures, compared with other climatic regions.

TABLE 1 A 3 × 3 factorial design was proposed for the exposure conditions (interventions), with the only independent variables temperature and CO_2 levels as indicators for the ventilation rates



Base line condition

	CO_2 = 600 ppm	CO_2 = 1000 ppm	CO_2 = 1800 ppm
Mild cold T1 = 20°C	Intervention 1: T = 20°C × CO_2 = 600 ppm	Intervention 2: T = 20°C × CO_2 = 1000 ppm	Intervention 3: T = 20°C × CO_2 = 1800 ppm
Neutral T2 = 23°C	Intervention 4: T = 23°C × CO_2 = 600 ppm	Intervention 5: T = 23°C × CO_2 = 1000 ppm	Intervention 6: T = 23°C × CO_2 = 1800 ppm
Mild warm T3 = 25°C	Intervention 7: T = 25°C × CO_2 = 600 ppm	Intervention 8: T = 25°C × CO_2 = 1000 ppm	Intervention 9: T = 25°C × CO_2 = 1800 ppm

The red color is referring to the base line condition of exposure to which all other conditions are compared to, it is important in the statistical analysis.

and 499 adult female students (age 16–23) successfully completed the experiments across nine intervention conditions determined by three settings of temperature and three settings of CO_2 levels, Table 1. A "washout" period was provided between the interventions by excluding the intervention during semester and summer break as well as examination periods to act as a break to eliminate the learning effect that can occur over the long period of this study. Temperature and CO_2 levels were controlled individually using the building management system (BMS), which have separate controllers for temperature and CO_2 levels independent of each other in the BMS control room.

Students were invited in large numbers since the intervention was intended to be conducted over a long duration of time, and it was therefore expected that not all the students would be able to participate in all of the nine times required. At the beginning of the study, 640 participants contributed, from which 627 came back for participation in the following intervention, followed by 618 participants. Afterward, 606 participants contributed followed by 596 participants, and then 581, followed by 564, and 551 participants afterward. Finally, 499 participants contributed to all interventions. Each intervention lasted for 5 weeks. Eight participants contributed at the same time, and an average of four experiments were conducted per day.

Two classrooms were selected since they were computer laboratories, and hence, performing the computerized neurobehavioral battery tasks on the available computers was easier and more feasible, also they were located in a central location which was not exposed to external heat radiation, and thus, the effect or radiant temperature was eliminated as well as the effect of sunlight. The windows were not openable, and they are recessed for solar shading with single glazing and are always shaded internally with blinds during daytime. The lighting units were distributed equally on both ceilings of the selected classrooms. Hence, the selection of the computers' location was in accordance with the location of the diffuser inlets and outlets. Afterwards, the participants were asked to begin the cognitive performance tests. Each cognitive performance test lasted for around 30 min. Another 5 min were provided for the participants to fill the questionnaires. Participants' behaviors were observed and recorded.

2.1 | Physical monitoring

Objective measurements were collected for air temperature, relative humidity, CO_2 concentration levels, noise levels, while lighting intensity was calculated given that no dimming was possible. A calibrated Telaire 7001 infrared gas monitor (accuracy: 50 ppm or 5% of the reading) was used for measuring CO_2 levels (as indicators for ventilation rates), a calibrated HOBO U12-013 data logger was used for measuring indoor temperature and relative humidity (range: 10%–90%, accuracy: ±2.5%), and a data logging sound level meter (range: 30–130 dB(A), accuracy: ±1.4 dB(A)) was used for measuring the sound levels. The equipment was located in a central location in the classrooms. This location was chosen since the outlets and inlets of the AC are distributed equally in the ceiling. Data were collected continuously from 8:00 a.m. until 4:00 p.m. The equipment was placed at the head height of a seated person. Classrooms were monitored under closed conditions. Simultaneously, the mean of daily outdoor temperature and relative humidity was monitored during the intervention study.

2.2 | Cognitive performance assessment

Cognitive performance assessment started after around 20 min from the time the participants entered the classroom to allow them enough time to become acclimatized to the exposure conditions. The Behavioral Assessment and Research System is the computer-based cognitive performance battery used in this study.[12] Tests used were as follows: Continuous performance (CPT) and simple reaction time (SRT) for attention, match-to-sample (MTS) for visual memory and delay, symbol digit (SDL), digit span (DST), and serial digit (SDT) for complex functions, alternating tapping (ALT TAP) for attention and coordination. '9Buttons' keyboards were used as they have the advantage of having only nine buttons (larger in size compared with the typical ones), the ones needed for the purpose of the given tasks and thus minimizing the distraction when selecting the right button as quickly as possible. Figure 1 shows the match-to-sample test as an example of the memory and complex tests. The outcome measures are percentages of errors and reaction time per seconds. The number of trials, duration of tasks, stimulus durations, interval between presentation of sample stimulus and distractors, success/fail criteria, and the number of spans at each length presented in the tasks in which digits are used were all kept constant for the nine times of exposures, therefore difficulty level and duration of the tasks were maintained, while the learning effect was offset for the accuracy of data analysis. The whole duration of the cognitive tests assessment lasted for no longer than 35 min. Overall exposure time lasted for ~60–70 min, that is, short-term exposure.

2.3 | Subjective measurements

On the day prior to the first exposure, participants attended a practice session to make sure that they understand the questionnaire's questions. The questionnaires were disseminated to the participants directly after they finished their cognitive performance assessment. TSV were collected. The rating scale used for TSV is based on the ASHRAE/ISO[13] seven-point thermal sensation scale, defined in the sample of the questionnaire (Figure 2).

2.4 | Data analysis

Descriptive analysis was performed to describe the individuals' pattern of cognitive performance, in terms of their accuracy and speed of performance providing means and standard deviations for continuous variables and percentages for the categorical. Due to the longitudinal design of the study, linear mixed effect models were used to explore the exposure conditions with the cognitive performance tasks to account for the repeated measures provided from the same students over the nine interventions. Univariable models explored the association between the potential confounders of this study (the ethnicity, number of years spent in the country for the non-Saudi participants, AC temperature set at home, the reported symptoms that impaired the focusing ability, and the reported intolerable thermal discomfort which lead to inability to focus) with the outcomes of interest. The factors that were found to be associated with accuracy and speed of performance in the univariable analysis ($p < 0.05$) were considered in the multivariable models for percentage of errors and speed of response. A two-tailed *p* test was used, *p*-value <0.05 was considered significant. Stata software Release 13 was used.

3 | RESULTS

The questionnaire responses indicated the following: 64% of the participants were ethnically Saudis. The average number of sleeping hours during the nights before participation was 7 h or more for 99% of the participants, 100% ate breakfast on all days of participation, and 99% of the participants did not drink caffeinated beverages within 2 h before participation. Only 1% reported being stressed for personal reasons. 2% were dissatisfied with the ambient noise during all conditions of exposure. 5% reported symptoms of dizziness, headache, and heaviness on their head, leading to the inability to focus during the exposure conditions when CO_2 levels were an average of ~600 ppm (20 l/s-p) and/or ~1000 ppm (7.5–8 l/s-p), while 95% reported having these symptoms in the exposure conditions when CO_2 levels reached ~1800 ppm (2.5–3 l/s-p). 99% of the participants reported having these symptoms during the intervention when the CO_2 levels were an average of ~1800 ppm (2.5–3 l/s-p) while the temperature was set at 25°C (intervention 9). 98% reported wearing clothes equivalent to 0.8 clo and 0.9 clo (49% for each) under "*Abaya*," a traditional dress of women worn on top of the clothes and mostly made of silk or light material. Only 2% were wearing clothes equivalent to 1.0 and/or 1.1 clo under "*Abaya*". 82% reported numbness in their fingers during the interventions when the temperature was set at 20°C, <1% reported numbness in fingers when the temperature was set at 23°C, and no one has reported numbness in fingers in any intervention when the temperature was set at 25°C.

It can be noted from Figure 3 that the frequency of Saudi participants who reported "Hot" thermal sensation during the interventions when the temperature was set at 25°C versus the non-Saudis, and more non-Saudi participants reported "Cold" during the interventions when the temperature was set at 20°C compared with the Saudi participants. Regarding the results of the final multivariable-multilevel model, Table 2 is presenting the effect percentages of errors after adjusting for the confounders showing the interactions (the combined effect of both; temperature and CO_2 levels as markers for ventilation rates) which are discussed thoroughly in a separate paper. To understand the association of thermal comfort, temperature, and ventilation rate, boxplots were plotted showing the distribution of errors and speed stratified by ventilation rate and temperature (Supporting Information). Figures 4 and 5 illustrate examples of the distribution of SRT error and speed, respectively, stratified by ventilation rate and temperature.

It can be noted that a higher percentage of errors occurred at higher temperature (25°C) whilst the participants perceiving the ambient thermal environment as "Hot" and also concurrent with poor ventilation rate (2.5–3 l/s-p at CO_2 = 1800 ppm) suggesting a synergetic effect of thermal comfort, temperature, and ventilation rate on SRT error. Regarding the speed, it can be noted that the slowed speed occurred at lower temperature (20°C) when the participants reported perceiving the ambient thermal environment as "Cold", "Slightly Cool," and "Cool," this was intensified with poorer ventilation rate (2.5–3 l/s-p at CO_2 = 1800 ppm) which confirmed the synergistic effect of thermal comfort, temperature, and ventilation rate on speed.

The results for the univariable statistical analysis indicated that age, physical activity, sleeping hours, caffeine, and stress owing to personal reasons, ambient noise, and clothing levels were not associated with the percentage of errors and speed of the cognitive tasks, therefore not included in the multivariable models. Tables 3 and 4 present the association of thermal comfort sensation with the cognitive tasks. This is to focus on the effects attributed to the thermal comfort sensations whilst the effects of the temperature

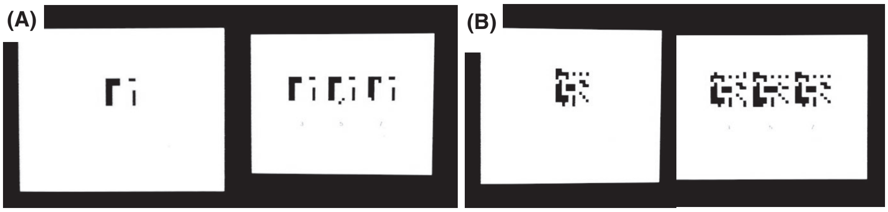


FIGURE 1 Match-to-sample task showing a variety of visual patterns starting with very easy patterns at the beginning of the test (A), then followed by more difficult patterns (B)

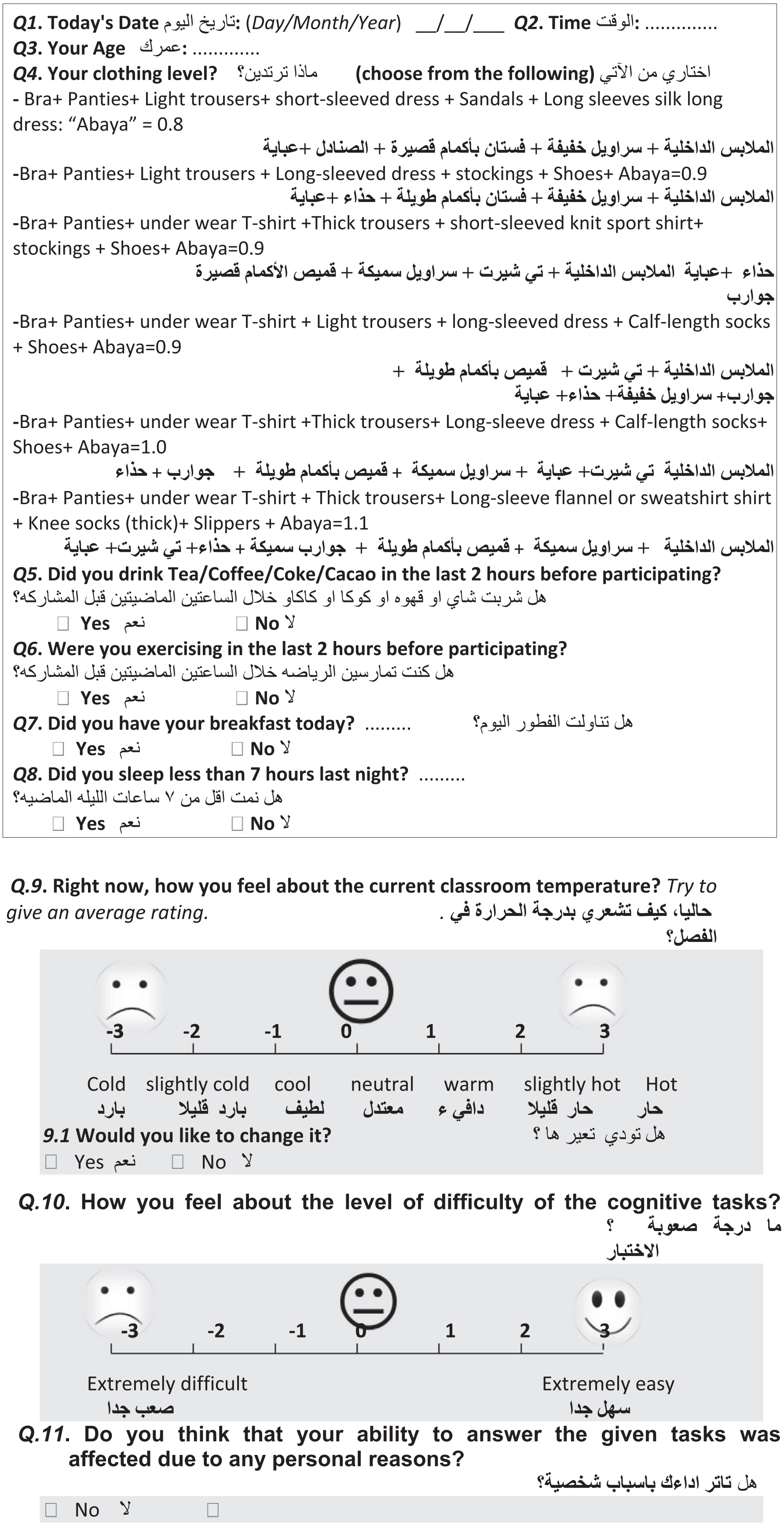
and ventilation rates are discussed thoroughly in a separate paper. The results consistently suggested that the percentage of error in the cognitive tasks was significantly lower for "Cool" and "Slightly Cool" thermal sensation compared with neutral. However, compared with neutral thermal sensation, feeling "Cold," "Warm," and "Hot" was associated with a significantly higher percentage of error for all cognitive tasks. Similarly, the multivariable regression models of Tables 4 and 5 show the association of the speed for completing the different cognitive tasks with thermal comfort sensation. The results suggested that "Cold" thermal sensation compared with neutral was associated with a significantly faster completion of the cognitive tasks while feeling "Warm" or "Hot" compared with neutral was associated with a significantly slower completion of all cognitive tasks, Tables 5 and 6; however, the faster performance was associated with higher percentages of errors.

4 | DISCUSSION

The results indicated lower percentages of errors for the thermal sensations of "Cool," "Slightly Cool," and "Slightly Warm" versus neutral for all tasks compared with the sensations of "Cold," "Warm," and "Hot". Gunstad et al.[14] suggested that cognitive functions are reduced during exposure to acute coldness. Hancock and Vasmatzidis[15] explained that cognitive performance can decrease due to the disturbance to the physiological stability when the body gets outside the psychological zone of maximal adaptability. In this regard of adaptation, Lan et al.[16] explained that in the absence of conscious effort, the human body might tend to adapt by lowering the internal heat production, and this reduces or even prevents perspiration which could be linked to the common experience that warmth makes one feel drowsy and relaxed and therefore work less efficiently. This can be linked to the arousal where Tham and Willem[4] reported lower arousal of the participants during moderate warm exposure and concluded that cooling sensation activates the brain and excites the nervous system controlling thermoregulation, and that the activation of the sympathetic nervous system elevates mental alertness or arousal. However, it is important to highlight that different cognitive tasks are accomplished by different dominant hemispheres and different brain cortexes. These tasks include memory, reasoning, and planning; however, attention functions differ from these functions in that they underlie and maintain the activity of the cognitive functions which can justify the discrepancy in the results obtained of the effects of thermal sensations on the vigilance tasks versus the memory tasks (Table 3). Also, this can also be linked to arousal where Kershaw and Lash[17] explained that attempting to maintain high arousal levels in unfavorable thermal environments can lead to fatigue and diminishing performance. Watanuki and Kim[18] revealed that exposure to moderate cold resulting in reduced comfort is believed to have the potential to activate the amygdala and can result in higher arousal, also Maula et al.[19] found that task-specific effort was significantly higher at a slightly warm temperature for a long-term memory task which can justify the negative effects observed on accuracy attributed to the hot and warm sensations. Lan et al.[20] suggest that moderately elevated temperatures should be avoided even if thermal comfort can be achieved as it may lead to reduced performance. Cui et al.[21] found that warm discomfort was more detrimental to performance than cold.

Regarding the speed of performance, significant faster performance was observed when the participants felt "Hot", "Slightly warm," and "Warm." Grether[22] explained that reaction time is sped up upon the exposure to the heat due to an increased speed of neural conduction associated with elevated body temperature. Hocking et al.[23] provided the explanation for the high speed by the theory of increased neural activity. Moreover, the results indicated that the speeds of reaction in all tasks were slowed down significantly at TSVs "Cold," "Cool," and "Slightly cool." Lan et al.[16] suggested that the slower speed at low temperature can be attributed to the deterioration of hands' dexterity due to joints' stiffening. A thorough explanation was provided by Lan et al.[16] on the speed-accuracy trade-off where the neurobehavioral tests in their laboratory experiment lasted only for 30 min, which was relatively very short time; however, the participants were encouraged to perform trying their best during such a duration (i.e., speed was adjusted to ensure low errors) especially that the nine neurobehavioral tests they investigated were not very difficult. Thus, they found it reasonable that the performance of many tasks was not affected significantly over a short period within the temperature range they investigated (19–32°C) referring to Ramsey and Kwon[24] who noted that the core temperature had a tendency to elevate slightly with continued exposure suggesting a continual deterioration in cognitive performance with prolonged exposure.

Contradictory results were reported in few studies which suggested that warm environment can be associated with reduced reaction time, for example, Holland et al.[25] reported increased task speed as the temperature ascended. However, findings were not consistent in their literature. Schiavon et al.[26] found that the participants had the fastest processing speed at 26°C compared with a cooler temperature of 23°C or warmer temperature of 29°C. Roelofsen,[27] Jensen et al.,[3] and Lan et al.[2] agreed that in a warm or



***Q1*. Today's Date تاريخ اليوم:** (*Day/Month/Year*) __/__/___ ***Q2*. Time الوقت:** ....

***Q3*. Your Age عمرك:** ....

***Q4*. Your clothing level?** ماذا ترتدين؟ **(choose from the following)** اختاري من الآتي

- Bra+ Panties+ Light trousers+ short-sleeved dress + Sandals + Long sleeves silk long dress: "Abaya" = 0.8

الملابس الداخلية + سراويل خفيفة + فستان بأكمام قصيرة + الصنادل +عباية

-Bra+ Panties+ Light trousers + Long-sleeved dress + stockings + Shoes+ Abaya=0.9

الملابس الداخلية + سراويل خفيفة + فستان بأكمام طويلة + حذاء +عباية

-Bra+ Panties+ under wear T-shirt +Thick trousers + short-sleeved knit sport shirt+ stockings + Shoes+ Abaya=0.9

حذاء +عباية الملابس الداخلية + تي شيرت + سراويل سميكة + قميص الأكمام قصيرة جوارب

-Bra+ Panties+ under wear T-shirt + Light trousers + long-sleeved dress + Calf-length socks + Shoes+ Abaya=0.9

الملابس الداخلية + تي شيرت + قميص بأكمام طويلة + جوارب+ سراويل خفيفة+ حذاء+ عباية

-Bra+ Panties+ under wear T-shirt +Thick trousers+ Long-sleeve dress + Calf-length socks+ Shoes+ Abaya=1.0

الملابس الداخلية تي شيرت+ عباية + سراويل سميكة + قميص بأكمام طويلة + جوارب + حذاء

-Bra+ Panties+ under wear T-shirt + Thick trousers+ Long-sleeve flannel or sweatshirt shirt + Knee socks (thick)+ Slippers + Abaya=1.1

الملابس الداخلية + سراويل سميكة + قميص بأكمام طويلة + جوارب سميكة + حذاء+ تي شيرت+ عباية

***Q5*. Did you drink Tea/Coffee/Coke/Cacao in the last 2 hours before participating?**
هل شربت شاي او قهوه او كوكا او كاكاو خلال الساعتين الماضيتين قبل المشاركه؟

☐ **Yes** نعم ☐ **No** لا

***Q6*. Were you exercising in the last 2 hours before participating?**
هل كنت تمارسين الرياضه خلال الساعتين الماضيتين قبل المشاركه؟

☐ **Yes** نعم ☐ **No** لا

***Q7*. Did you have your breakfast today?** .... هل تناولت الفطور اليوم؟

☐ **Yes** نعم ☐ **No** لا

***Q8*. Did you sleep less than 7 hours last night?** ....
هل نمت اقل من ٧ ساعات الليله الماضيه؟

☐ **Yes** نعم ☐ **No** لا

***Q.9*. Right now, how you feel about the current classroom temperature?** *Try to give an average rating.* **حاليا، كيف تشعري بدرجة الحرارة في . الفصل؟**

-3	-2	-1	0	1	2	3
Cold	slightly cold	cool	neutral	warm	slightly hot	Hot
بارد	بارد قليلا	لطيف	معتدل	دافي ء	حار قليلا	حار

***9.1* Would you like to change it?** هل تودي تعير ها ؟

☐ Yes نعم ☐ No لا

***Q.10*. How you feel about the level of difficulty of the cognitive tasks?** **ما درجة صعوبة الاختبار ؟**

-3	-2	-1	0	1	2	3
Extremely difficult						Extremely easy
صعب جدا						سهل جدا

***Q.11*. Do you think that your ability to answer the given tasks was affected due to any personal reasons?**
هل تاثر اداءك باسباب شخصية؟

☐ No لا ☐

FIGURE 2 Sample of the questionnaire survey disseminated to the participants

FIGURE 3 Frequencies of the intervention study (IS) votes from (A) Saudi versus (B) non-Saudi participants

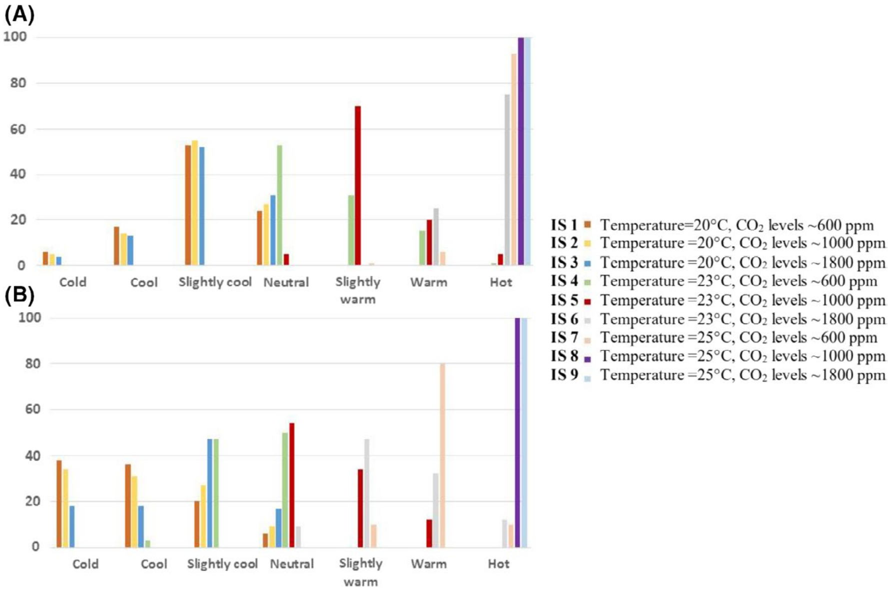


TABLE 2 Estimated effect size on the accuracy of tasks (percentages of errors) after adjusting for confounders showing the interactions (the combined effect of both; temperature, and CO_2 levels as indicators for ventilation rates simultaneously)

	SRT % of errors		RL % of errors	
Variable	***β*-coeff. (95% CI)**	***p*-value**	***β*-coeff. (95% CI)**	***p*-value**
Temperature/°C				
23°C versus 20°C	5.4 (4.8, 6.0)	<0.001	−2.3 (−3.8, −1.8)	<0.001
25°C versus 20°C	11.3 (10.9, 11.6)	<0.001	7.1 (6.6, 8.4)	<0.001
CO_2 level/ppm				
1000 ppm versus 600 ppm	6.5 (6.3, 7.2)	<0.001	6.7 (5.2, 7.2)	<0.001
1800 ppm versus 600 ppm	10.2 (10.0, 10.9)	<0.001	10.9 (9.6, 11.3)	<0.001
Interactions				
1000 ppm versus 600 ppm, $T = 23°C$ versus 20°C	2.4 (0.8, 4.2)	<0.001	11.8 (9.3, 12.8)	<0.001
1000 ppm versus 600 ppm, $T = 25°C$ versus 20°C	4.5 (3.0, 5.3)	<0.001	13.7 (11.3, 15.4)	<0.001
1800 ppm versus 600 ppm, $T = 23°C$ versus 20°C	3.9 (1.6, 5.0)	<0.001	17.2 (14.8, 18.9)	<0.001
1800 ppm versus 600 ppm, $T = 25°C$ versus 20°C	14.6 (12.9, 16.3)	<0.001	18.5 (16.0, 22.1)	<0.001

These models are adjusted for the confounding factors namely: ethnicity, number of years spent in the country (for the non-Saudi participants), thermal comfort sensations, air-conditioner's set temperature at home, symptoms of headache, dizziness, heaviness on head, confusion, difficulty thinking, difficulty concentrating and fatigue, and intolerable thermal discomfort attributable to an inability to focus

Interventions	
IS 1	Temperature =20°C, CO_2 levels ~600 ppm
IS 2	Temperature =20°C, CO_2 levels ~1000 ppm
IS 3	Temperature =20°C, CO_2 levels ~1800 ppm
IS 4	Temperature =230°C, CO_2 levels ~600 ppm
IS 5	Temperature =23°C, CO_2 levels ~1000 ppm
IS 6	Temperature =23°C, CO_2 levels ~1800 ppm
IS 7	Temperature =25°C, CO_2 levels ~600 ppm
IS 8	Temperature =25°C, CO_2 levels ~1000 ppm
IS 9	Temperature =25°C, CO_2 levels ~1800 ppm

Abbreviation: RL, reversal learning; SRT, simple reaction time.

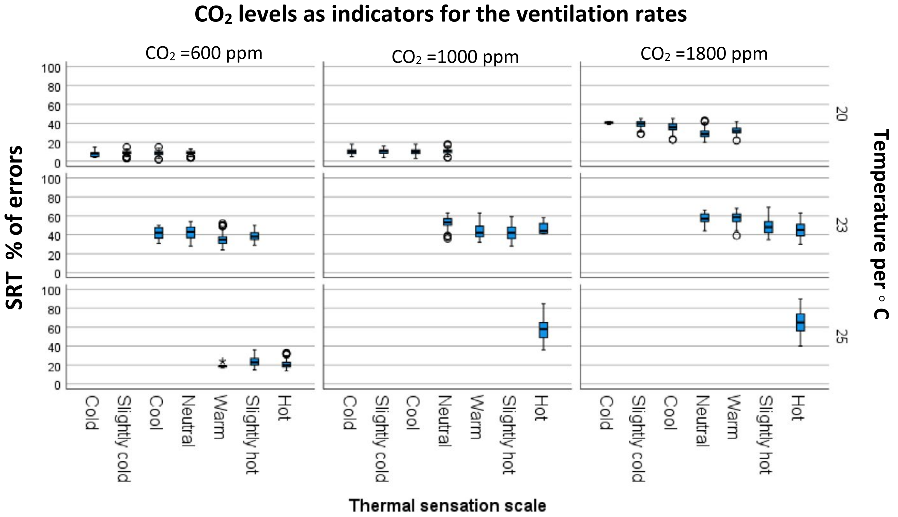


FIGURE 4 Boxplot for the simple reaction time (SRT) test as an example showing the distribution of data after taking in consideration the effects of temperature, CO_2 levels (as indicators for the ventilation rates) and thermal comfort sensations on the percentage of errors

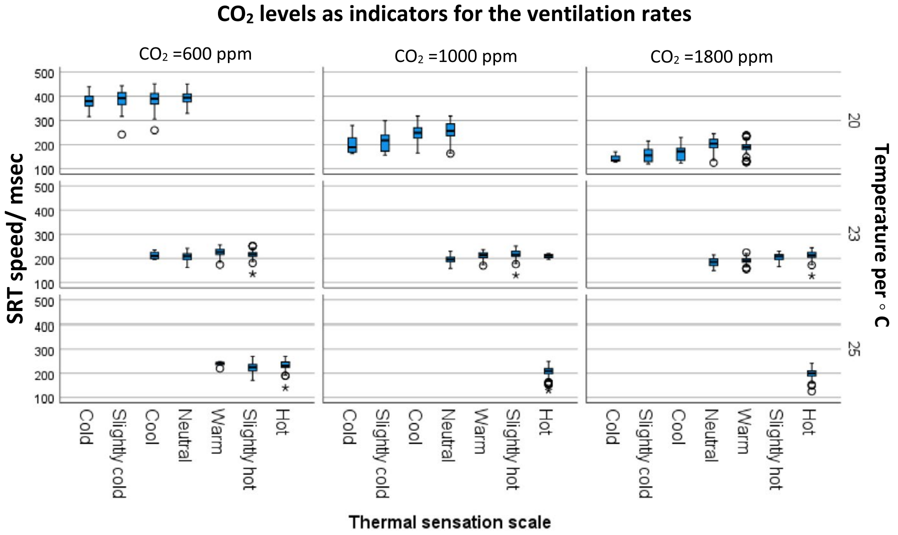


FIGURE 5 Boxplot for the simple reaction time (SRT) test as an example showing the distribution of data after taking in consideration the effects of temperature, CO_2 levels (as indicators for the ventilation rates) and thermal comfort sensations on the speed of performance

cold discomfort environment, the learning rate was slowed down. This dissimilarity could be justified therefore by the effects attributed to the thermal sensations and not absolute temperatures which varies according to the climatic context and was found correlated to occupants' habits of setting the temperature of AC at home.

It is worth highlighting that the effect of exposure time of this study which lasted for around 1 h per exposure. In the studies of Wargocki and Wyon[6] and Bako Biro et al.,[28] the exposures lasted for a week but the tests they used were shorter. Therefore, this can be considered as a limitation of the study as it is still unclear whether the effects will prevail at the same or different levels if the exposure lasted for longer and whether the exposures should be repeated every day for a week or for a month and thus future research is needed to investigate this. Therefore, the results obtained are relevant for short-term exposures lasting no more than 2 h.

By weaving the insights from the data presented, and the associations obtained between ethnicity, number of year spent in the country for the non-Saudis, and the AC set temperature at home and the statistical analysis results and the questionnaires responses which indicated that Saudi's TSVs varied significantly compared with the non-Saudis,' hence, one can imply a synergetic effect of the investigated temperatures, CO_2 levels as markers for the ventilation rates and thermal sensations. This is supported by the higher percentage of errors which occurred at higher temperature (25°C) when the participants perceived the ambient thermal environment as “Hot,” which was also concurrent with poor ventilation rate (2.5–3 l/s-p at CO_2 = 1800 ppm). Also, the slowed speed which occurred at lower temperature (20°C) when the participants reported perceiving the and ambient thermal environment as “Cold,” “Slightly Cool,” and “Cool,” can support the synergetic effect, particularly that the slow speed was intensified with poorer ventilation rate (2.5–3 l/s-p at CO_2 = 1800 ppm).

One can also suggest that ethnicity played a big role in this study. Ewing and Lan Yong[29] and Rivkin et al.[30] observed differences between ethnic groups in terms of temperature preference while learning which may support the effect of ethnicity. Furthermore, the inclusion of the confounder of AC temperature at home in the final statistical model resulted in a significant decrease in the percentages of errors for every 1°C increase in the range between 18–24°C.

According to participants' TSVs, the mean AC temperature set by the Saudi participants at home was lower by 2°C relative to the non-Saudis. Acclimation studies agreed that people who have AC acclimation behavior at home are perceiving thermal neutrality with lower temperatures compared with the non-acclimatized people within the same climatic context. This study suggests that participants' TSVs varied considerably by ethnicity.

Figure 3 indicated that for the Saudis, exposure to 23°C attributed to "Cool" and/or "Slightly Cool" at 20°C, and "Slightly Warm" at 23°C, while at 25°C almost all participants felt uncomfortably "Hot." However, the non-Saudi participants perceived the thermal environment as "Slightly Cool" and/or neutral at 23°C while the non-Saudis reported feeling "Cold," and "Cool" at 20°C, and fewer reported feeling "Hot" at 25°C relative to the Saudis. Therefore, a stratified univariable thermal comfort analysis by ethnicity was performed for participants' TSVs. It was found that during interventions 1 and 2 (Temp. = 20°C, CO_2 levels = 600 ppm (20 l/s-p) and 1000 ppm (7.5–8 l/s-p), respectively), the non-Saudi participants reported a "Cold" thermal sensation while the Saudis did not. Based on Table 4, "Cold" TSV was attributed to ~10% increase in the percentage of errors as an average estimate size from all tasks. However, during interventions 4 and 5 (Temp. = 23°C, CO_2 levels = 600 ppm (20 l/s-p) and 1000 ppm (7.5–8 l/s-p), respectively), the Saudi participants reported "Slightly Warm," "Warm," and "Hot" TSVs whereas the non-Saudis reported "Cool," "Slightly Cool," "Slightly Warm," which were found to be associated with a significant decrease in the percentage of errors. According to de-Dear and Brager,[31] adaptation to the thermal environment, physiological, and past thermal exposure experience play a crucial role in human's thermal comfort sensation. In the notion of adaptation in real life classrooms which can

TABLE 3 Association of thermal comfort sensation with the cognitive tasks: SRT, RL, MTS, and CPT[a]

	SRT[a] (error%) β-coeff. (95% CI)	*p*-value	RL[a] (error%) β-coeff. (95% CI)	*p*-value	MTS[a] (error%) β-coeff (95% CI)	*p*-value	CPT[a] (error%) β-coeff (95% CI)	*p*-value
Thermal comfort sensation								
Neutral	Ref.		Ref.		Ref.		Ref.	
Cold	6.6 (5.1, 7.0)	<0.001	10.7 (9.1, 11.4)	<0.001	13.1 (12.2, 14.9)	<0.001	5.7 (4.1, 6.3)	0.003
Cool	−1.5 (−2.2, −0.3)	<0.001	−0.9 (−1.5, −0.4)	<0.001	−1.1 (−1.5, −0.4)	<0.001	−1.7 (−2.3, −0.2)	0.002
Slightly cool	−2.5 (−3.6, −1.0)	0.001	−1.8 (−2.6, −0.1)	0.003	−2.5 (−3.4, −1.5)	0.001	−2.1 (−3.2, −1.0)	0.008
Slightly warm	5.0 (4.5, 6.6)	0.005	−0.5 (−0.3, −0.8)	<0.001	−0.6 (−1.1, −0.2)	<0.001	5.2 (4.5, 6.9)	0.003
Warm	6.1 (5.5, 7.7)	0.004	8.2 (7.1, 9.9)	<0.001	8.8 (7.3, 9.9)	<0.001	7.5 (6.0, 8.1)	0.007
Hot	9.5 (8.3, 10.3)	<0.001	14.0 (13.0, 15.9)	<0.001	16.1 (15.6, 17.6)	<0.001	10.9 (9.9, 11.8)	0.003

Abbreviations: CPT, continuous performance; MTS, match-to-sample; SRT, simple reaction time.

[a] Models are adjusted for temperature, ventilation rate, ethnicity, number of years spent in the country (for the non-Saudi participants), AC's set temperature at home, symptoms of headache, dizziness, heaviness on head, confusion, difficulty thinking, difficulty concentrating and fatigue, and intolerable thermal discomfort attributable to an inability to focus.

TABLE 4 Association of thermal comfort sensation with the errors of the cognitive tasks: SDT, SDL, DST, and ALT[a]

	SDT[a] (error%) β-coeff. (95% CI)	*p*-value	SDL[a] (error%) β-coeff. (95% CI)	*p*-value	DST[a] (error%) estimate (95% CI)	*p*-value	ALT[a] TAP (error%) estimate (95% CI)	*p*-value
Thermal comfort sensation								
Neutral	Ref.		Ref.		Ref.		Ref.	
Cold	10.4 (9.7, 11.1)	<0.001	14.3 (13.6, 15.9)	<0.001	14.3 (13.7, 15.9)	<0.001	7.4 (6.4, 8.4)	<0.001
Cool	−0.9 (−0.4, −0.3)	<0.001	−1.4 (−2.6, −0.1)	<0.001	−2.5 (−6.0, 1.0)	<0.001	6.7 (5.5, 7.2)	0.002
Slightly cool	−2.8 (−3.6, −1.0)	0.002	−2.3 (−3.4, −1.2)	0.004	−3.3 (−4.9, −2.2)	<0.001	−1.7 (−2.7, −0.6)	0.001
Slightly warm	−0.5 (−0.5, −0.6)	<0.001	−0.2 (−0.1, −0.5)	<0.001	−0.2 (−0.4, −0.8)	0.003	−4.8 (−5.7, −4.0)	<0.001
Warm	8.4 (7.1, 9.9)	0.001	13.9 (12.2, 14.3)	0.009	13.9 (12.4, 14.5)	0.006	5.1 (4.5, 6.7)	<0.001
Hot	12.7 (11.3, 13.1)	<0.001	20.1 (19.8, 21.4)	0.001	20.8 (19.6, 21.9)	0.008	9.6 (8.4, 10.1)	<0.001

Abbreviations: ALT TAB, alternating tapping; DST, digit span; SDL, symbol digit; SDT, serial digit.

[a] Models are adjusted for temperature, ventilation rate, ethnicity, number of years spent in the country (for the non-Saudi participants), air-conditioner's set temperature at home, symptoms of headache, dizziness, heaviness on head, confusion, difficulty thinking, difficulty concentrating and fatigue, and intolerable thermal discomfort attributable to an inability to focus.

TABLE 5 Association of thermal comfort sensation with the speed of the cognitive tasks: SRT, RL, MTS, and CPT[a]

	SRT[a] (speed/s) *β*-coeff. (95% CI)	*p*-value	RL[a] (speed/s) *β*-coeff. (95% CI)	*p*-value	MTS[a] (speed/s) *β*-coeff. (95% CI)	*p*-value	CPT[a] (speed/s) *β*-coeff. (95% CI)	*p*-value
Thermal comfort sensation								
Neutral	Ref.		Ref.		Ref.		Ref.	
Cold	2.5 (1.2, 3.2)	0.005	2.6 (1.1, 3.1)	0.007	2.2 (0.6, 3.7)	0.008	3.5 (0.7, 6.3)	0.007
Cool	1.0 (0.6, 3.7)	0.100	1.6 (0.3, 2.4)	0.005	1.1 (−1.0, 3.3)	0.005	1.5 (−0.3, 3.2)	0.005
Slightly cool	0.5 (0.2, 2.6)	0.100	1.5 (0.1, 2.6)	0.100	0.9 (−0.7, 2.6)	0.100	1.2 (−1.2, 3.7)	0.100
Slightly warm	−11.0 (−15.3, −6.8)	0.001	−13.1 (−15.2, −11.1)	0.100	−10.2 (−12.5, −8.0)	0.100	−10.0 (−12.5, −8.4)	0.100
Warm	−20.5 (−22.3, −18.7)	0.001	−15.9 (−17.8, −13.0)	0.001	−15.1 (−17.6, −12.5)	0.001	−13.2 (−15.7, −11.0)	0.001
Hot	−27.5 (−29.7, −25.3)	0.001	−20.4 (−21.1, −19.3)	0.001	−25.5 (−27.8, −22.8)	0.001	−15.8 (−17.6, −13.1)	0.001

Abbreviations: CPT, continuous performance; MTS, match-to-sample; SRT, simple reaction time.

[a] Models are adjusted for temperature, ventilation rate, ethnicity, number of years spent in the country (for the non-Saudi participants), AC's set temperature at home, symptoms of headache, dizziness, heaviness on head, confusion, difficulty thinking, difficulty concentrating and fatigue, and intolerable thermal discomfort attributable to an inability to focus.

TABLE 6 Association of thermal comfort sensation with the speed of the cognitive tasks: SDT, SDL, DST, and ALT[a]

Variable	SDT[a] (speed/s) *β*-coeff. (95% CI)	*p*-value	SDL[a] (speed/s) *β*-coeff. (95% CI)	*p*-value	DST[a] (speed/s) *β*-coeff. (95% CI)	*p*-value	ALT TAP[a] (speed/s) *β*-coeff. (95% CI)	*p*-value
Thermal comfort sensation								
Neutral	Ref.		Ref.		Ref.		Ref.	
Cold	4.6 (3.2, 2.1)	0.005	4.9 (3.2, 5.7)	0.005	9.8 (6.3, 13.2)	0.005	4.2 (2.4, 5.9)	0.005
Cool	2.3 (1.8, 3.9)	0.005	2.9 (1.7, 3.1)	0.100	6.0 (3.2, 8.9)	0.100	3.2 (1.7, 4.6)	0.100
Slightly cool	1.5 (0.4, 2.9)	0.100	1.4 (2.3, 0.9)	0.100	4.5 (0.3, 9.2)	0.100	1.2 (1.2, 3.7)	0.100
Slightly warm	−10.5 (−15.2, −5.8)	0.100	−17.4 (−24.8, −9.9)	<0.001	−13.9 (−16.9, −11.1)	<0.001	−6.4 (−7.9, −4.9)	0.001
Warm	−15.2 (−18.9, −12.4)	0.001	−28.8 (−31.4, −25.1)	<0.001	−31.7 (−35.3, −28.1)	<0.001	−14.4 (−16.2, −12.5)	0.001
Hot	−20.5 (−22.9, −18.1)	0.001	−37.8 (−42.6, −32.9)	<0.001	−40.8 (−46.4, −35.2)	0.006	−19.3 (−22.1, −16.4)	0.001

Abbreviations: ALT TAB, alternating tapping; DST, digit span; SDL, symbol digit; SDT, serial digit.

[a] Models are adjusted for temperature, ventilation rate, ethnicity, number of years spent in the country (for the non-Saudi participants), air-conditioner's set temperature at home, symptoms of headache, dizziness, heaviness on head, confusion, difficulty thinking, difficulty concentrating and fatigue, and intolerable thermal discomfort attributable to an inability to focus.

depend on the exposure time, in this study exposure time lasted for ~60–70 min, which is the average duration of lectures in universities in Saudi Arabia (based on the field observation while intervening) which indicate that the attributed effects observed are considered valid to be representative to the effects in real life world. However, these results are relevant for short-term exposures lasting no more than 2 h.

Regarding the self-reported symptoms (dizziness, headache of participants, and heaviness on participants' heads which inhibited their focusing ability), The results indicated that the percentage of errors increased by an average of 15% for all tasks, and the speed was increased by an average of 17 s for those who reported the symptoms. Amin et al.[32] investigated thermal conditions and SBS symptoms in air-conditioned engineering education laboratories in Malaysia and showed that majority of the students have experienced SBS symptoms, namely: dry skin (41%), runny nose (31%), dry eyes (30%), blocked/stuffy nose (28%), tiredness (27%), and flu-like symptoms (21%). They suggested that the reported SBS symptoms are due to the use of AC, where the conditions of indoor air movement and relative humidity in air-conditioned spaces may expose occupants to dust, mold, chemicals, and contaminants. Mentese et al.[33] found correlations among the occurrence of SBS symptoms, measured indoor pollutants, and comfort parameters ($p < 0.05$). Therefore, it can be implied that the reported symptoms are more likely to be attributed to the effects of the high CO_2 as indicators for the poor ventilation rates. It is important to highlight that in this study, CO_2 was the bio-effluent from the participants and controlled via ventilation where no other pollutants were monitored, therefore, it cannot be excluded that some of the effects observed at certain CO_2 levels were due to other pollutants. The effects attributed to changes in ventilation rates, controlled by CO_2 levels, are discussed thoroughly in a separate paper.

5 | CONCLUSIONS

This study considered the effect of thermal sensations and acclimatization in Jeddah, Saudi Arabia, among a society which is heavily reliant on mechanical cooling. Discrepancies in the TSV between Saudi and non-Saudi participants were noted which were found to be associated with the speed and the percentage of errors of the cognitive tasks considered in this study. The factor of ethnicity was found responsible for the preference of the Saudi participants to a lower temperature relative to the non-Saudis by ~2°C; however, further research is needed to confirm whether this is due to physiological acclimatization and/or cultural differences. Multivariable multilevel statistical analysis was used and after accounting for the possible confounders, "Cold" sensation was associated with a significant increase in the percentage of errors by ~11% for both memory and vigilance tasks while the "Slightly Cool" and "Cool" sensations were associated with significant lower percentage of errors for these tasks. 'Hot' sensation was associated with a significant increase in the percentage of errors by ~22% for memory tasks and ~16% for vigilance tasks. "Slightly Warm" sensation attributed to a significant increase in the percentage of errors but only for the vigilance tasks while for the memory tasks the percentage of errors decreased significantly concluding that thermal sensations affect vigilance and memory tasks differently. Regarding the speed, the slowest response was associated with the "Cold" sensation compared with "Hot" and "Warm." Nevertheless, the slowest performance and the higher percentages of errors occurred at poor ventilation rates suggesting a synergetic effect of thermal sensations and the investigated temperatures and the CO_2 levels (used as markers for the ventilation rates) and the cognitive performance of participants in the context of this study. Also, the results imply that "Cool" and "Slight Cool" sensations may be conducive to accuracy but not speed, independently of acclimatization status. However, these results are relevant for short-term exposures lasting no more than 2 h.

AUTHOR CONTRIBUTIONS

Riham Ahmed involved in conceptualization-Lead, data Curation-Lead, formal analysis-Lead, investigation-Lead, methodology-Lead, project administration-Lead, resources-Lead, and writing—original and final drafts-Lead. Marcella Ucci involved in supervision-Lead, validation-Lead. Dejan Mumovic involved in supervision-Lead and validation-Lead. Emmanouil Bagkeris involved in formal analysis-Supporting, software-Supporting.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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