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Combined effects of ventilation rates and indoor temperatures on cognitive performance of female higher education students in a hot climate

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Abstract

Impairment in mental functions attributed to the effects of indoor air quality and thermal conditions has received considerable attention in the past decade, particularly for educational buildings where students' cognitive performance is essential to foster learning. This study explores the combined effects of indoor temperatures and CO_2 levels as markers for ventilation rates on cognitive performance among female students (16–23 years old) in Saudi Arabia. The longitudinal experiments involved nine conditions combining three CO_2 concentration levels (achieved via changes in ventilation) and three temperature levels involving 499 participants, all exposed to the nine conditions. The study implemented a computer-based cognitive performance battery with "9Button" keyboards. Univariable and multivariable multilevel regression models explored the association of indoor temperature and CO_2 levels (as markers for ventilation rates) with cognitive performance after adjusting for potential confounders. Potential benefits were found on speed and accuracy of tasks of cognitive performance when indoor temperature was set between 20 and 23°C and at CO_2 levels of 600 ppm compared to higher temperatures and poorer ventilation rates and that both ventilation and thermal environmental control are important and need to be improved for achieving optimum learning conditions. Nevertheless, the results are relevant for short-term exposures lasting no more than 2 h.

KEYWORDS
air-conditioned buildings, cognitive performance, educational buildings, hot climates, indoor air quality, ventilation

1 | INTRODUCTION

Educational buildings are complex spaces to design as they need to perform well in all aspects of environmental conditions while needing to accommodate periods with very high occupant densities, which result in high internal heat gains, high carbon dioxide (CO_2) levels, elevated concentrations of body odors and, potentially, various indoor pollutants. Maintaining thermal conditions and ventilation rates within certain ranges, however, is associated with an energy penalty, which is particularly undesirable in the light of climate change mitigation objectives. Therefore, in order to adequately evaluate the significance of potential reductions in cognitive or academic performance due to poor indoor environmental quality against potential energy and carbon emissions implications, it is important to correctly estimate the magnitude of effects while accounting for potential confounding factors. Furthermore, while several studies have assessed the impact of temperature and/or ventilation rates on cognitive performance within educational settings, there is limited data relevant to university buildings. Nevertheless, findings from school buildings research provide evidence that there is a correlation between students' performance and CO_2 concentrations in classrooms (e.g., Refs. [1] and [2]). It was also indicated that CO_2 levels, as markers for the ventilation rates, which exceed the recommended level by ASHRAE of 1000 ppm can cause a reduction in the students' performance assessed by short-term computer-based tests (e.g., Ref. [3]). Coley and Greeves[1] found that increased levels of CO_2 from a mean of 690 ppm to a mean of 2909 ppm led to a significant reduction in attention by about 5% on primary school children. Wargocki et al.[2] suggest that increasing the ventilation rate in classrooms in the range from 2 to 10 L/s-person can bring significant benefits in terms of learning performance and pupil attendance. Nevertheless, results from adults' studies like Satish et al.[4] who investigated the direct effects of CO_2 (by injecting ultrapure CO_2 in an office-like chamber) found that at 1000 and 2500 ppm, a significant reduction in decision-making performance occurred compared with 600 ppm. Also, Allen et al.[5] obtained similar results in an office-like setting for adults, noting effects of CO_2 on cognitive performance independently of ventilation rates. Scarce data is available to date on the CO_2 levels as markers for ventilation rates in classrooms of educational buildings in Saudi Arabia, and no evidence is obtained on the effect of ventilation on the performance of adult students in this context. Hence, this study is focusing particularly on this aspect.

Furthermore, not only CO_2 as a marker for ventilation rates is associated with productivity, but also most of the effects reported from relevant studies have demonstrated that the percentage of error and speed were affected by temperature, particularly for vigilance, reasoning and memory tasks (e.g., Ref. [6]). Wargocki and Wyon[7] and Bakó-Biró et al.[8] had a robust experimental design using cross-sectional blind interventions. In principle, cognitive performance evaluations focus mainly on two aspects of human performance: speed and accuracy. Bakó-Biró et al.[8] investigated the effect of temperature on cognitive performance in the range between 23 and 25°C. The analysis of their results suggested an improvement by about 6%–8% when lowering the temperature from 25.3 to 23.1°C. They used computer-based cognitive performance tests with standard keyboards, while Wargocki and Wyon[7] used pen-and-paper academic performance tests. Performance tests represented different aspects of school work including language-based and numerical tests. Another robust meta-analysis study by Wargocki et al.[9] used data from 18 studies to construct a relationship between thermal conditions in classrooms and children's performance in school. The relationship derived suggested that school tasks can be expected to increase by 20% on average if classroom temperatures are lowered from 30 to 20°C and that the temperature for optimal performance is lower than 22°C. Also, Lan et al.[10] investigated the effect of room temperature on performance of neurobehavioral tests in the laboratory. Four temperatures were investigated (19, 24, 27, and 32°C). It was concluded that room temperature affected the performance of tests differentially, depending on the type of task. The accuracy of most tests peaked at 24°C or at 27°C relative to 19°C and 32°C. Nevertheless, the results from Wargocki et al.[9] are only valid for temperate climates. Therefore, this paper primarily focuses on the hot climatic context of Saudi Arabia, where limited data is available.

The driving idea was that young adults in higher education (age 16–23) living year-round in air-conditioned spaces (home, transport, and university) are likely to develop high expectations for homogeneity and cool temperatures and may become more sensitive if thermal conditions deviate from the comfort zone they have come to expect. Furthermore, for cultural reasons the dress code of females in Saudi Arabia is fairly standardized: therefore, there are limited opportunities for adaptive thermal comfort via clothing level adjustments. The study also include a number of methodological advances: (a) longitudinal blind intervention experimental design with nine intervention conditions involving 499 participants, (b) implementation of a computer-based cognitive performance battery with "9Button" keyboard minimizing distraction to search for the right button (and increasing accuracy of "speed of response" measurements), (c) implementation of a multivariable multilevel statistical modelling approach, which is suitable for repeated measurements within the same study participants for exploring the association of combinations of indoor temperature and CO_2 levels as markers for ventilation rates on cognitive performance after controlling for potential confounders.

Practical Implications

This study demonstrates that there is a strong association between indoor temperature, CO_2 levels (as markers for ventilation rates and indicators for indoor air quality) and cognitive performance in young adult female (age 16–23), and that limiting indoor CO_2 levels to 600 ppm (~20 L/s-p) may be beneficial, since the cognitive performance of young adult female students started to deteriorate at higher CO_2 levels for vigilance and memory tasks. The practical implications of this study include the need for performance-based building regulations for educational buildings in Saudi Arabia, which would enable the building industry to design, construct, and operate educational buildings conducive to learning.

2 | METHODS

Phase 1: Establishing the appropriate exposure conditions. In order to do so, a brief questionnaire was disseminated to 450 schools and six universities in Jeddah asking about the set Air Conditioner temperature in classrooms during the academic semesters. Also, information about the baseline indoor temperatures and CO_2 levels as markers for ventilation rates in 25 classrooms in the selected case study building were collected over a period of 3 weeks. 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 limitation of time and resources, CO_2 levels (as markers for ventilation rates) were not collected at this stage. Phase 2: Conducting a pilot study (lasted for 9 weeks) in the case study building. This is to examine the feasibility of adopting the proposed methodological approach, technical capability of the building service system to maintain the required indoor temperatures and ventilation rates need for specific CO_2 levels within the selected classrooms. Within-subject design was applied. Each exposure condition lasted for 1 week. Thirty participants successfully completed Phase 2. Phase 3: Conducting an intervention study in the selected case study building, namely in two identical classrooms. This lasted for 12 months exclusive of semester breaks and examination periods which acted as a "washout" period between the interventions to exclude the learning effect that may occur. 499 participants successfully completed the experiments across the nine interventions.

2.1 | Exposure conditions and classrooms' characteristics

Indoor temperature and CO_2 levels, as markers for ventilation rates, were the only independent variables which were manipulated via the classroom's heating/cooling and ventilation systems. Sound levels, lighting intensity, and relative humidity were kept within constant ranges during the exposure conditions. Nine exposure conditions were investigated combining temperatures and CO_2 levels, as markers for ventilation rates, controlled by the Building Management System (BMS). Three indoor temperatures set points were selected: 20, 23, and 25°C. This was based on the following criteria: the results of the short questionnaire and monitoring carried out during Phase 1, and the technical capabilities of the building services systems in the selected classrooms to maintain the required temperature during the intervention study. The ventilation rates were set up to achieve CO_2 levels at 600, 1000, and 1800 ppm (corresponding to 20 L/s-p, 7.5–8 L/s-p, and 2.5–3 L/s-p respectively for ventilation rates) based on experiments during Phases 1 and 2. CO_2 levels of 1000 ppm represented the reference according to the existing guidelines for acceptable Indoor air quality in educational buildings defined by the ASHRAE standards.[11] CO_2 levels of 600 ppm were selected as the baseline condition since a number of relevant studies have referred to the significant impairment of decision-making skills and cognitive performance at elevated CO_2 concentrations compared to 600 ppm, for example, Satish et al.[4] CO_2 levels of 1800 ppm were found to be the maximum levels of CO_2 that could be achieved during Phase 2 without injecting CO_2 in to the classrooms. For achieving the CO_2 levels within the required range, the BMS was used by modulating the fresh air dampers, exhaust dampers, and return dampers together to reach the desired CO_2 set points required. For achieving CO_2 levels within ranges of 1800 ppm, the damper of the fresh air was shut by the BMS, thus putting the command of the dampers in manual mode, which caused the dampers to no longer be controlled by the BMS. The intervention study (IS) investigated the combined exposure conditions of indoor temperatures and CO_2 levels, as markers for ventilation rates, in a 3 × 3 factorial design as follows: IS1 (Baseline condition): Temp.: 20°C × CO_2: 600 ppm/ventilation: 20 L/s-p, IS2: Temp.: 20°C × CO_2: 1000 ppm/ventilation: 7.5–8 L/s-p, IS3: Temp.: 20°C × CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p, IS4: Temp.: 23°C × CO_2: 600 ppm/ventilation: 20 L/s-p, IS5: Temp.: 23°C × CO_2: 1000 ppm/ventilation: 7.5–8 L/s-p, IS6: Temp.: 23°C × CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p, IS7: Temp.: 25°C × CO_2: 600 ppm/ventilation: 20 L/s-p, IS8: Temp.: 25°C × CO_2: 1000 ppm, and IS9: Temp.: 25°C × CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p. Regarding the baseline CO_2 levels as markers for ventilation in classrooms in the educational buildings in Jeddah for adult females, due to practicality reasons and time and money constraints, it was not possible to gather this information from the educational buildings in Jeddah; however, 25 classrooms in the case study building were monitored prior to the intervention and the pilot study. Based on the information gathered, the baseline CO_2 levels was found to be in the range of 600 ppm (20 L/s-p). The temperature of 20°C was selected as a baseline condition since it was found to be the most common temperature set in more than 75% of the educational buildings surveyed prior to the intervention study (338 secondary schools out of the total number of 450 schools, and all of the university buildings which were surveyed). Two classrooms were selected based on the following: (a) access to sufficient number of power sockets to support computer-based cognitive performance testing, (b) located on the inner side of building with no walls exposed to direct sunlight to minimize the effect of radiant temperature and glare, and (c) located at the end of the corridor to minimize the noise distraction from the passing students. The air conditioner system in the building is a central CAV system (supplying constant air volume). Ventilation in these rooms is solely via air diffusers from the ceiling from the mechanical ventilation system. The commissioning of Air Handling Units (AHU) was set at 25% supply of outdoor fresh air of the design value. It is worth noting that it was not possible to set the supply of outdoor fresh air at 100% since 25% supply of outdoor fresh air is the maximum that can be set on the building management system used. Nevertheless, it is known that this arrangement most likely provided a minimum flow much higher than required because of the non-linear relationship between flow and damper stroke, especially if the dampers are oversized. Therefore, it was assured that this was sufficient to provide the minimum requirement of outdoor air supply that complies with ASHRAE Standard 62.1–2019.[11] Air is returned to the AHUs via ceiling return air diffusers.

TABLE 1 Summary of the schedule of the interventions, and the number of participants who participated in each intervention

Sequence of exposures	IS 1	IS 5	IS 3	IS 2	IS 9	IS 6	IS 7	IS 8	IS 4
Number of weeks	5	5	5	5	5	5	5	5	5
Number of participants	640	627	618	606	596	581	564	551	499
Number of interventions	640	627 × 2 = 1254	618 × 3 = 1854	606 × 4 = 2424	596 × 5 = 2980	581 × 6 = 3486	564 × 7 = 3948	551 × 8 = 4408	499 × 9 = 4491

Abbreviation: IS, intervention study.

2.2 | Recruitment considerations

Four hundred ninety-nine participants were exposed to all exposure conditions, where each participant performed the cognitive performance test nine times. The participants were invited to contribute in the first exposure condition/intervention and after 5 weeks, the participation for the first conditions was closed and the participants were invited to contribute in the following intervention. All participants were exposed to the same conditions in the same order of exposure shown in Table 1 where this sequence was chosen based on observations from the pilot study. During the pilot study (in which the order of IS was from 1 to 9), over 80% of participants (*N* = 25 out of 30) found that the last four exposure exposures were the least favored which lead to increased rate of withdrawal during the last 3 weeks. These participants reported that the main reason for their withdrawal was that they have noticed that the exposure conditions were changing from unfavored conditions to worse. Therefore, it was decided to change the order of exposure in the interventions in a way that would be uneasy for the participants to predict the forthcoming ones to minimize/limit the discourage of the participants as much as possible.

It was made clear that participation was based on the participants' free will. All participants invited were non-smokers, aged 16–23 years, and were expected to be available throughout the whole intervention duration. To increase motivation, community service hours were offered (a requirement by the university to encourage citizens to benefit their community).

2.3 | Intervention study execution

Due to limited availability of the "9Button" keyboards, only eight participants were tested at the same time. Four experiments were conducted per day in each classroom, where two classrooms were used for the study. The participants arrived 30 min before performing the cognitive test to allow time to adapt to the classroom adjusted exposure conditions. During the pilot study the participants who were sitting directly under the air diffusers reported heaviness on their head and headache and were unable to finish the tasks; therefore, the position of all "9Button" stations addressed this observation. The lighting units were distributed equally on the ceilings. On the day prior to the first exposure, the participants attended a practice session and were instructed to forgo their morning coffee on the days of the study, and not to drink soda, energy drinks, and avoid eating chocolate which are proven to influence humans' cognitive performances (e.g., Ref. [12]). They were also instructed to avoid intense physical activity for at least 12 h prior to participation. No restrictions were given on the worn clothing levels. The participants were exposed to the different exposure conditions on the same weekday to avoid any influence of weekday on the within-subject difference between conditions. No testing was done before lunchtime to avoid the likeliness of hunger, which was found to lower the blood flow rate[13] and thus contributing to the sensation of being cold regardless of the ambient temperature. The exposure conditions were introduced to the participants using a blind intervention approach. The cognitive tests lasted for around 30 min, so in total the exposure time lasted for ~60 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. Each exposure condition lasted for ~5 weeks, which covered exposure of all participants. To ensure that the learning effect was removed, in addition to the wash-out period which was kept between the interventions, the parameters of the cognitive tasks were modified with each time of the exposure in terms of the order of the tasks, sequence of the appearance of stimuli in each task, their shapes, their corresponding response keys. Hence, difficulty level and duration of the tasks were maintained while learning effect was offset for the accuracy of data analysis. The order of the intervention studies was set in the order stated in Table 1 so that the less favored conditions of high temperature and/or elevated CO_2 levels are not investigated towards the end of the intervention, based on an observation noted from the pilot study when the participants noticed that the exposure conditions were changing to become worse towards the end when they started from IS1 to IS9 which discouraged them from coming back.

2.4 | The climatic conditions and monitoring of environmental parameters

The climatic context plays the primary role in choosing Saudi Arabia for this study. This research was conducted in Jeddah, the second largest population in Saudi Arabia after the capital Riyadh. Table 2 presents the measured physical parameters during the different exposure conditions investigated in the study in both classrooms.

The calculated lighting intensity was 400 Lux. Indoor temperature and relative humidity (RH) were monitored using HOBO U12 (Temp.: range: −20 to 50°C, accuracy: ±0.2°C from 0 to 50°C), (RH: range: 0%–100% RH, accuracy: ±2.5% from 10% to 90% RH, resolution 0.05% RH). CO_2 were monitored using TelAire7001 infrared gas monitor (accuracy: ±50 ppm or 5% of the reading), Ambient sound levels were monitored using Data-logging Sound Level Meter [range: 30–130 dB(A), accuracy: ±1.4 dB(A)]. The data were recorded at 5-min intervals, and located in line with ANSI/ASHRAE 55-2020 Standard.[14] Simultaneously, the mean of daily outdoor temperature was monitored during the intervention study. These instruments were calibrated before being used.

2.5 | Subjective measurements: Questionnaires

Thermal Sensation Votes were collected, using the ASHRAE/ISO seven-point thermal sensation scale, defined as hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (−1), cool (−2) and cold (−3). The questionnaire included a question about participants' clothing level at the time of participation (choices were provided based on the most likely combinations that could be worn by the participants in their context). There was no restriction on adjusting the clothing attires when necessary for achieving and maintaining thermal neutrality. The questions asked about the confounders of the study were as follows: participants' age, ethnic background, how many years they have lived in Saudi Arabia, and their level of physical activity in general and whether the participants performed any kind of physical activity within 2 h prior to participation, and/or if they had a caffeinated beverage within 2 h of participation, and/or if they had breakfast on the same day of participation, and how many sleeping hours they had during the night before participation, their use of air conditioners at home was included to account for the potential physiological habituation to the cold, the difficulty level of the cognitive tests was also included, and whether the participants were feeling stressed, whether the self-reported intolerable thermal discomfort was

TABLE 2 Measured environmental parameters (mean ± SD) during the interventions

	Temperature (°C)		CO_2 levels (ppm)		RH (%)		Air velocity from diffusers (m/s)		Noise levels (dB(A))	
	Room 1	Room 2	Room 1	Room 2	Room 1	Room 2	Room 1	Room 2	Room 1	Room 2
IS 1	19.8 ± 0.2	19.9 ± 0.2	592 ± 15	596 ± 18	45	45	0.15 ± 0.1	0.16 ± 0.1	38 ± 3	36 ± 3
IS 2	20.2 ± 0.2	20.1 ± 0.2	1007 ± 24	1010 ± 27	45	45	0.16 ± 0.1	0.15 ± 0.2	36 ± 3	35 ± 3
IS 3	20.4 ± 0.1	20.3 ± 0.2	1816 ± 36	1812 ± 30	44	44	0.14 ± 0.1	0.15 ± 0.1	33 ± 2	34 ± 3
IS 4	23.1 ± 0.2	23.2 ± 0.1	609 ± 21	612 ± 22	43	43	0.12 ± 0.2	0.13 ± 0.1	35 ± 3	36 ± 3
IS 5	23.3 ± 0.1	23.3 ± 0.1	1005 ± 25	1011 ± 29	43	43	0.11 ± 0.1	0.11 ± 0.1	35 ± 3	35 ± 3
IS 6	23.3 ± 0.1	23.3 ± 0.2	1821 ± 43	1817 ± 36	42	43	0.11 ± 0.1	0.10 ± 0.1	35 ± 2	35 ± 3
IS 7	24.9 ± 0.1	25.1 ± 0.2	614 ± 26	602 ± 15	41	41	0.09 ± 0.1	0.09 ± 0.1	36 ± 3	37 ± 3
IS 8	25.1 ± 0.2	25.1 ± 0.2	1016 ± 35	1009 ± 31	39	39	0.10 ± 0.1	0.09 ± 0.1	33 ± 2	32 ± 2
IS 9	25.3 ± 0.1	25.2 ± 0.2	1823 ± 45	1820 ± 40	39	39	0.08 ± 0.1	0.08 ± 0.1	34 ± 2	33 ± 2

Abbreviations: IS, intervention study; RH, relative humidity; SD, standard deviation.

leading to focus impairment, whether they detected dexterity in figures, and whether they detected sick building syndromes (SBS) symptoms like headache and fatigue when CO_2 levels were high since high CO_2 levels have been associated with subjectively assessed acute health symptoms in some studies, for example, Apte et al.[15] and Norbäck et al.[16]

2.6 | Cognitive performance assessment

The Behavioural Assessment and Research System (BARS) is the computer based cognitive performance battery used in this study. Copyright of the BARS testing system software is held by Oregon Health Sciences University. Eight neurobehavioral tasks were used (Table 3), and an example for one of the tests (reversal learning [RL]) is shown in Figure 1.

The "9Button" driver/keyboard (Figure 2) were used to enable the advantage of having only nine buttons to minimize distraction when selecting the buttons as quickly as possible.

2.7 | Data analysis

Descriptive analysis (means and standard deviation) was performed to describe the individuals' pattern of cognitive performance for all cognitive tasks. Due to the longitudinal design of the study, linear mixed effect models were used to explore the association of temperature and CO_2 as an indicator for ventilation rates with the cognitive performance tasks to account for the repeated measures provided from the same students over the nine interventions. Univariable models were performed to explore the association between the potential confounders of this study (namely: ethnicity, number of years spent in the country for non-Saudi participants, air-conditioner's temperature set at home, the reported symptoms that impaired the focusing ability, and the reported intolerable thermal discomfort leading to inability to focus) with accuracy and speed of performance. The factors that were associated with accuracy and speed of performance in the univariable analysis ($p < 0.05$) were considered in the multivariable models. A two-tailed *p* test was used, *p*-value less than 0.05 was considered significant. Stata software Release 13 was used: StataCorp LP.

3 | RESULTS

The measured physical parameters are presented in Table 2, and the outdoor temperature was found to be within a narrow range between 37 and 40°C which can be explained by the fact the interventions were conducted during academic semesters during which the variation in seasons' climatic conditions in Jeddah is very limited compared with summer.[17] The interventions were avoided during the summer break when temperature peaks in Jeddah[17] which excludes the effects on the results due to changes in the environmental conditions, seasons' variations and changes in the outdoor climatic conditions.

The questionnaire survey indicated that 64% of the participants were ethnically from Saudi Arabia. All study participants

TABLE 3 Summary of the cognitive tasks used in this study

Test	Symbol	Function measured
Continuous Performance	CPT	Sustained attention (Vigilance)
Match-to-Sample	MST	Learning, and visual-memory capacity
Simple Reaction Time	SRT	Selective attention (Vigilance)
Reversal Learning	RL	Learning, coordination and working memory
Serial Digit	SDT	Learning, and digital memory capacity
Symbol Digit	SDL	Complex function of working memory
Digit Span	DST	Learning and complex function of working memory
Alternative Tapping	ALT TAP	Alternating attention, and coordination between right and left hemispheres of the brain (Vigilance)

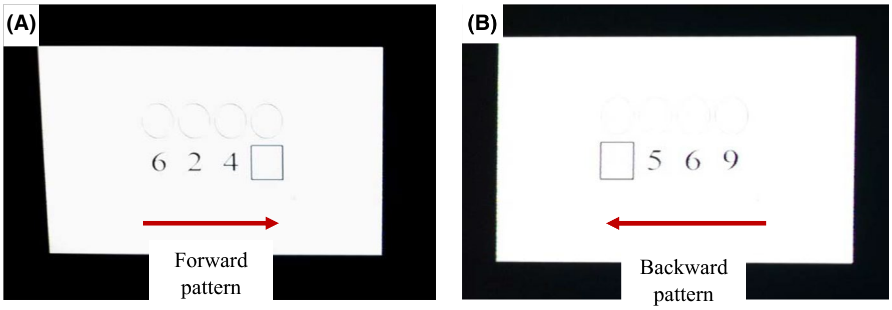

FIGURE 1 An example of the reversal learning (RL) test where the numbers have disappeared and the participant is required to retrieve the digits back in forward and backward patterns

were non-smokers, were not consuming alcohol, had no diagnosis of diabetes and had no chronic diseases. It was indicated from the questionnaires that: (a) 99% of the participants had ≥7 h of sleep the night before the test, (b) all have eaten breakfast, (c) 99% of the participants did not have caffeinated beverages within 2 h before participation, (d) 0.8% of the participants reported being stressed for personal reasons, and (e) no variation in the worn clothing levels of the university's uniform policy was reported. Less than 5% of the participants reported symptoms of dizziness, headache, and heaviness on their head which lead to the inability to focus during the exposure conditions when CO_2 levels were set at ~600 ppm/ventilation: 20 L/s-p and/or ~1000 ppm/ventilation: 7.5–8 L/s-p, while 95% reported these symptoms in the exposure conditions when CO_2 levels reached ~1800 ppm/ventilation: 2.5–3 L/s-p, and all participants reported these symptoms when the CO_2 levels were in average of ~1800 ppm while temperature was set at 25°C (IS9).

It was indicated by the descriptive analysis that the pattern of change in both; the accuracy (represented as percentage of errors) and speed across all attention tasks (Simple Reaction Time [SRT], Continuous Performance Test [CPT] and Alternative Tapping [ALT TAP]) and learnings/complex tasks (Reversal Learning [RL], Match-to-Sample [MTS], Symbol Digit [SDT], Serial Digit Learning [SDL], and Digit Span [DST]) is similar for the nine interventions. Specifically, for all attention and all learning/complex tasks the percentage of error was significantly higher at higher CO_2 levels and higher temperatures. With regards to speed, it was found that the students were significantly slower for all attention and all learning/complex tasks for higher levels of CO_2 and higher temperatures. The results of the linear multivariable multilevel models suggested that the percentages of errors increased significantly during all interventions relative to the baseline condition (IS1) (Temp.: 20°C × CO_2: 600 ppm/ventilation: 20 L/s-p) after adding the estimated effect sizes of the confounding variables to the original model except for IS4 (Temp.: 23°C × CO_2: 600 ppm/ventilation: 20 L/s-p), at which the percentages of errors decreased significantly but only for the memory and learning tasks. Also, it was noted that a higher magnitude of the effect on the accuracy of all tasks occurred particularly during the intervention IS9 (Temp.: 25°C × CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p) for all tasks compared with all other interventions. Regarding the speed, the results showed that the speed of reaction increased significantly during all interventions relative to IS1 (Temp.: 20°C × CO_2: 600 ppm/ventilation: 20 L/s-p)—the base line condition. To understand the combined effect of both temperature and CO_2 levels, as markers for the ventilation rates, on the percentages of errors and the speed of cognitive tasks, stratified boxplots were plotted. It was noted that the significant increase in the speed of response was concurrent with a significant increase in the percentages of errors and that it was intensified when temperature increased and ventilation decreased. This pattern was systematic across all cognitive tasks. An interaction model was done to quantify the effects of the temperatures and ventilation rates together after correcting for the confounding factors (e.g., Figures 3–6).

FIGURE 2 The “9Button” driver/keyboard (photo courtesy of the researcher)

The results of the statistical models after adjusting for the confounders are presented in Tables 4 and 5 showing the interactions, that is, the combined effects. For instance, for the SRT when temperature increased to 23 versus 20°C, the percentages of errors increased by 5.4%. When the CO_2 levels increased to 1000 versus 600 ppm, the percentages of errors increased by 6.5%. An additional 2.6% increase in the percentages of errors occurred due to the combined effect of temperature and CO_2. The total effect of this combination (5.4 + 6.5 + 2.6) is 14.5% which in other words is the effect

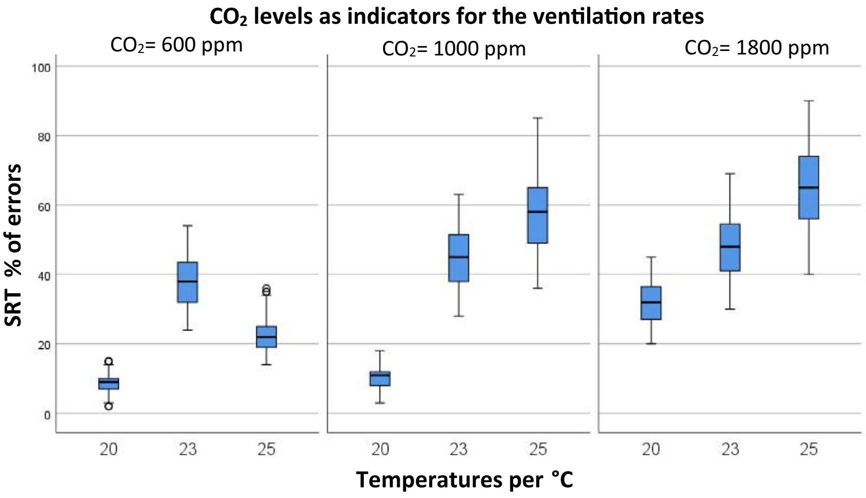

FIGURE 3 Boxplots to illustrate the pattern of the change of the combined effects of temperature and CO_2 levels as an indicator for the ventilation rates on the percentage of errors for the SRT test as an example for the attention tests. SRT, Simple Reaction Time

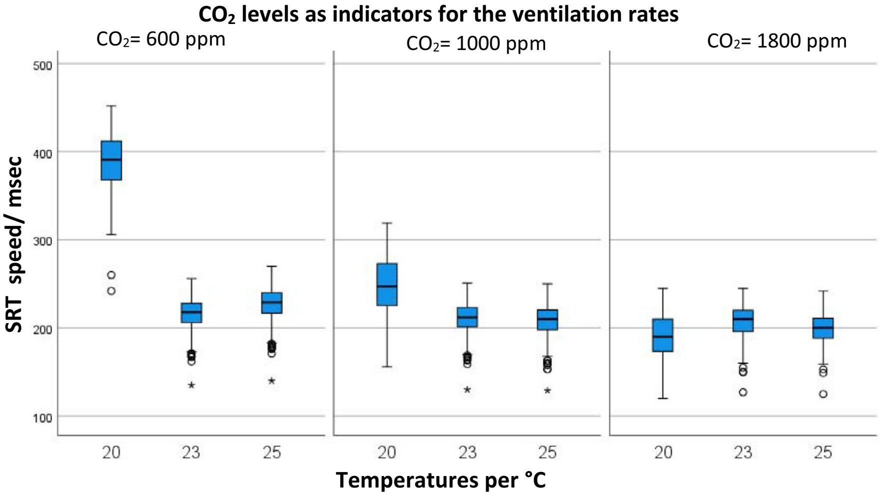

FIGURE 4 Boxplots to illustrate the pattern of the change of the combined effects of temperature and CO_2 levels as an indicator for the ventilation rates on the speed of performance for the SRT test as an example for the attention tests. SRT, Simple Reaction Time

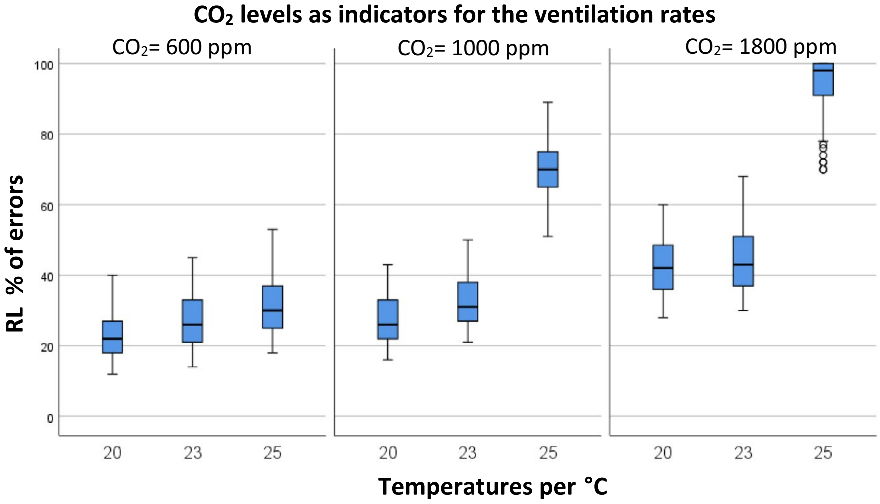

FIGURE 5 Boxplots to illustrate the pattern of the change of the combined effects of temperature and CO_2 levels as an indicator for the ventilation rates on accuracy for the RL test as an example for the memory/complex tests. RL, reverse learning

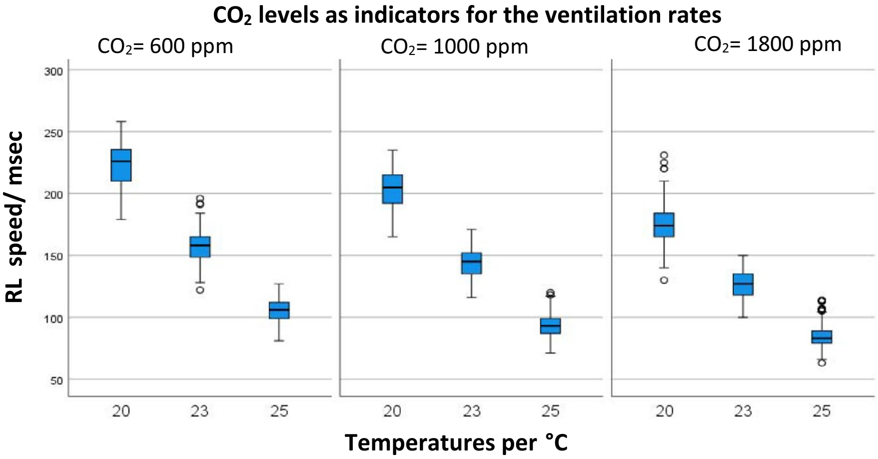

FIGURE 6 Boxplots to illustrate the pattern of the change of the combined effects of temperature and CO_2 levels as an indicator for the ventilation rates on accuracy for the RL test as an example for the memory/complex tests. RL, reverse learning

occurred at IS5 (Temp.: 23°C × CO_2: 1000 ppm) versus IS1 (Temp.: 20°C × CO_2: 600 ppm). It is important to note that the association of temperature and CO_2 with the accuracy and speed of all tasks of cognitive performance was independent of any association with thermal comfort, ethnicity, and acclimatization.

4 | DISCUSSION

The results indicated a discrepancy in the pattern of change of the percentage of errors between the vigilance and memory/learning and complex tasks suggesting that temperature and CO_2 levels, as

TABLE 4 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 vs. 20	5.4 (4.8, 6.0)	<0.001	−2.3 (−3.8, −1.8)	<0.001
25 vs. 20	11.3 (10.9, 11.6)	<0.001	7.1 (6.6, 8.4)	<0.001
CO_2 level (ppm)				
1000 vs. 600	6.5 (6.3, 7.2)	<0.001	6.7 (5.2, 7.2)	<0.001
1800 vs. 600	10.2 (10.0, 10.9)	<0.001	10.9 (9.6, 11.3)	<0.001
Interactions				
1000 vs. 600 ppm, *T* = 23 vs. 20°C	2.6 (0.8, 4.2)	<0.001	11.8 (9.3, 12.8)	<0.001
1000 vs. 600 ppm, *T* = 25 vs. 20°C	4.5 (3.0, 5.3)	<0.001	13.7 (11.3, 15.4)	<0.001
1800 vs. 600 ppm, *T* = 23 vs. 20°C	3.9 (1.6, 5.0)	<0.001	17.2 (14.8, 18.9)	<0.001
1800 vs. 600 ppm, *T* = 25 vs. 20°C	14.6 (12.9, 16.3)	<0.001	18.5 (16.0, 22.1)	<0.001
	MTS % of errors		**CPT % of errors**	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
Temperature (°C)				
23 vs. 20	−2.9 (−3.49, −1.3)	<0.001	6.2 (5.8, 6.6)	<0.001
25 vs. 20	10.3 (9.8, 11.8)	<0.001	11.4 (10.0, 12.9)	<0.001
CO_2 level (ppm)				
1000 vs. 600	7.8 (6.4, 8.2)	<0.001	7.4 (6.2, 8.6)	<0.001
1800 vs. 600	11.9 (10.4, 12.4)	<0.001	10.8 (9.6, 12.0)	<0.001
Interactions				
1000 vs. 600 ppm, *T* = 23 vs. 20°C	11.8 (9.7, 13.1)	<0.001	1.6 (0.8, 2.9)	<0.001
1000 vs. 600 ppm, *T* = 25 vs. 20°C	9.9 (7.2, 11.7)	<0.001	4.1 (2.4, 6.6)	<0.001
1800 vs. 600 ppm, *T* = 23 vs. 20°C	12.3 (9.8, 14.3)	<0.001	3.7 (1.7, 5.9)	<0.001
1800 vs. 600 ppm, *T* = 25 vs. 20°C	14.6 (12.5, 17.0)	<0.001	12.9 (10.0, 14.2)	<0.001
	SDT % of errors		**SDL % of errors**	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
Temperature (°C)				
23 vs. 20	−2.5 (−3.9, −1.1)	<0.001	−2.7 (−3.1, −1.3)	<0.001
25 vs. 20	9.9 (8.6, 10.3)	<0.001	8.7 (7.7, 9.7)	<0.001
CO_2 level (ppm)				
1000 vs. 600	6.8 (5.4, 7.1)	<0.001	8.5 (7.6, 9.5)	<0.001
1800 vs. 600	11.4 (10.1, 12.8)	<0.001	12.6 (11.5, 13.5)	<0.001
Interactions				
1000 vs. 600 ppm, *T* = 23 vs. 20°C	10.6 (8.3, 12.4)	<0.001	12.6 (10.4, 14.2)	<0.001
1000 vs. 600 ppm, *T* = 25 vs. 20°C	11.2 (9.1, 13.2)	<0.001	18.3 (15.9, 20.5)	<0.001
1800 vs. 600 ppm, *T* = 23 vs. 20°C	11.1 (9.3, 13.4)	<0.001	16.7 (13.9, 18.5)	<0.001
1800 vs. 600 ppm, *T* = 25 vs. 20°C	16.7 (13.6, 18.7)	<0.001	19.3 (16.2, 22.9)	<0.001
	DST % of errors		**ALT TAB % of errors**	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
Temperature (°C)				
23 vs. 20	−2.7 (−3.4, −1.3)	<0.001	4.7 (4.0, 5.4)	<0.001
25 vs. 20	9.1 (8.6, 10.7)	<0.001	8.8 (7.6, 9.0)	<0.001

(Continues)

TABLE 4 (Continued)

Variable	DST % of errors β-coeff. (95% CI)	*p*-value	ALT TAB % of errors β-coeff. (95% CI)	*p*-value
CO_2 level (ppm)				
1000 vs. 600	8.4 (7.4, 9.5)	<0.001	6.9 (5.2, 7.7)	<0.001
1800 vs. 600	12.4 (11.8, 13.9)	<0.001	10.2 (9.9, 11.4)	<0.001
Interactions				
1000 vs. 600 ppm, $T = 23$ vs. 20°C	15.3 (13.0, 16.4)	<0.001	1.3 (0.0, 2.1)	<0.001
1000 vs. 600 ppm, $T = 25$ vs. 20°C	17.5 (26.6, 28.4)	<0.001	4.2 (2.3, 6.4)	<0.001
1800 vs. 600 ppm, $T = 23$ vs. 20°C	17.4 (14.3, 18.8)	<0.001	3.6 (1.9, 6.0)	<0.001
1800 vs. 600 ppm, $T = 25$ vs. 20°C	18.5 (15.6, 20.1)	<0.001	10.7 (8.6, 12.7)	<0.001

Note: 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, 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.

Abbreviations: CI, confidence interval; CPT, Continuous Performance Test; DST, Digit Span; DSTRL, reversal learning; MTS, Match-to-Sample; SDL, Serial Digit Learning; SDT, Symbol Digit; SRT, Simple Reaction Time.

markers for ventilation rates, may affect memory and vigilance differently. For instance, regarding the effects of temperature only, Table 4 indicated that the percentage of errors decreased significantly only during the interventions when the temperature was set at 23 versus 20°C; however, this was for only the memory and complex tasks unlike the vigilance tasks for which the percentage of errors increased significantly during all interventions when the temperature was set at 23 and 25 versus 20°C. Lan et al.[10] who adopted a similar neurobehavioral approach (however, in their study only temperature was the only variable), they suggested that temperature effect is most likely task dependent referring to the fact that different tasks are accomplished by different dominant hemispheres and different brain cortices.[18] Seppänen et al.[19] reported that increasing temperature within 20–23°C may improve work performance while any increase beyond this range may lead to negative productivity and Wargocki and Wyon[20] showed that avoiding elevated temperatures would improve educational attainment.

Nevertheless, for the effects ventilation rates only, significantly higher percentage of errors was observed during all interventions when the CO_2 levels were set at 1800 ppm versus 1000 ppm (2.5–3 vs. 7.5–8 L/s-p) which agree with Twardella et al.[21] who reported a significant increase in the percentage of errors of concentration tasks on students when ventilation changed by increasing CO_2 levels from 1000 to 2000 ppm and also in line with other studies which used a similar approach of not considering CO_2 a pollutant but an indicator of the efficiency of ventilation when the main sources of CO_2 is the humans, for example, Coley and Greeves.[1] The results also agree with Bakó-Biró et al.[8] despite the difference in exposure time; however, the present study can add that ventilation rates are required in the order of 20 L/s-p not 7.5–8 L/s-p as they suggested. Wargocki et al.[22] found that ventilation rates below 10 1/s-p results in lower air quality and worsening of health problems. Also, the risk of sick building syndrome is reduced and the perceived air quality is improved when the ventilation rates increase from ~10 to 20 L/s-p. In this study, the questionnaire responses indicated that 99% of the participants reported symptoms of dizziness, headache, and heaviness on their head, leading to the inability to focus during the interventions with poor ventilation rates which supports the conclusion that the observed effects are more likely to be due to the effects of CO_2. Wargocki et al.[23] explained that in the absence of fresh air, the rate of metabolic CO_2 production of participants becomes higher and thus more likely to exert less effort. It is important to highlight that positive associations were noted between the percentages of errors and some symptoms which were detected via the questionnaires like headache, difficulty concentrating and fatigue. These detected symptoms corresponded with significantly higher percentage of errors during the interventions when temperature was set at 25°C and CO_2 of 1000 ppm (ventilation: 7.5–8 L/s-p) and even higher percentage of errors at CO_2 levels of 1800 ppm (ventilation: 2.5–3 L/s-p). Maula et al.[24] also found that these symptoms increased significantly at 29 versus 23°C which can support the results of the questionnaires. This also concurs with Apte et al.[15] who agreed that with increased CO_2 levels, significant associations were observed with headache, fatigue, eye, nose, and respiratory tract symptoms. Therefore, this strengthens the suggestion made that the observed effects are attributable to the pollutants that CO_2 is a proxy for; herein lies the scope of the study which is to investigate the effects of ventilation rates and not pure CO_2 levels.

By looking at the combined effect of both temperature and ventilation rates, it can be suggested from the results that participants' tolerance and adaptability increased up to 23°C, after which the accuracy declined significantly for all tasks at 25°C. Hancock and Vasmatzidis[25] provided an explanation that cognitive performance can decrease because of the disturbance to the physiological stability when the body gets outside the psychological zone of maximal adaptability. Accordingly, a suggestion can be made that temperature range for optimum accuracy in performance for vigilance and memory tasks could be 20–23°C but this is only valid at higher ventilation rate with CO_2 levels of 600 ppm (~20 L/s-p), Figure 7 (modified from the relation derived by Hancock and Vasmatzidis,[25] and Yerkes

TABLE 5 Estimated effect size on the speed of performance after adjusting for confounders showing the interactions (the combined effect of both; temperature and CO_2 levels as indicators for ventilation rates simultaneously)

	SRT speed/s		**RL speed/s**	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
Temperature (°C)				
23 vs. 20	−70.5 (−88.5, −62.5)	<0.001	−46.3 (−55.5, −37.0)	<0.001
25 vs. 20	−110.2 (−128.3 −92.2)	<0.001	−87.9 (−97.1, −78.6)	<0.001
CO_2 level (ppm)				
1000 vs. 600	−53.6 (−61.6, −45.6)	<0.001	−30.2 (−41.5, −19.0)	<0.001
1800 vs. 600	−82.5 (−100.6, −74.5)	<0.001	−70.0 (−79.2, −50.8)	<0.001
Interactions				
1000 vs. 600 ppm, *T* = 23 vs. 20°C	−64.1 (−72.1, −56.5)	<0.001	−10.6 (−12.0, −8.8)	<0.001
1000 vs. 600 ppm, *T* = 25 vs. 20°C	−55.0 (−61.6, −45.9)	<0.001	−37.4 (−45.8, −32.6)	<0.001
1800 vs. 600 ppm, *T* = 23 vs. 20°C	−42.4 (−49.5, −51.8)	<0.001	−30.0 (−40.7, −21.5)	<0.001
1800 vs. 600 ppm, *T* = 25 vs. 20°C	−70.1 (−84.6, −58.9)	<0.001	−42.2 (−49.5, −30.3)	<0.001

	MTS speed/s		**CPT speed/s**	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
Temperature (°C)				
23 vs. 20	−7.2 (−8.4, −6.1)	<0.001	−21.7 (−30.9, −28.3)	<0.001
25 vs. 20	−41.6 (−52.8, −30.5)	<0.001	−44.1 (−45.4, −42.8)	<0.001
CO_2 level (ppm)				
1000 vs. 600	−12.9 (−20.1, −37.8)	<0.001	−19.2 (−23.5, −16.9)	<0.001
1800 vs. 600	−23.9 (−28.1, −15.8)	<0.001	−35.0 (−39.3, −31.7)	<0.001
Interactions				
1000 vs. 600 ppm, *T* = 23 vs. 20°C	−8.4 (−11.2, −5.9)	<0.001	−12.6 (−17.2, −9.5)	<0.001
1000 vs. 600 ppm, *T* = 25 vs. 20°C	−34.4 (−41.0, −27.8)	<0.001	−21.1 (−27.7, −18.0)	<0.001
1800 vs. 600 ppm, *T* = 23 vs. 20°C	−24.6 (−33.1, −19.8)	<0.001	−15.5 (−22.0, −11.3)	<0.001
1800 vs. 600 ppm, *T* = 25 vs. 20°C	−80.2 (−94.1, −70.8)	<0.001	−30.9 (−37.8, −25.2)	<0.001

	SDT speed/s		**SDL speed/s**	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
Temperature (°C)				
23 vs. 20	−36.2 (−47.6, −25.8)	<0.001	−84.8 (−90.8, −77.7)	<0.001
25 vs. 20	−70.5 (−73.1, −68.0)	<0.001	−135.7 (−141.8, −128.6)	<0.001
CO_2 level (ppm)				
1000 vs. 600	−19.2 (−25.7, −15.6)	<0.001	−55.3 (−62.3, −42.2)	<0.001
1800 vs. 600	−57.5 (−65.1, −52.0)	<0.001	−91.4 (−100.5, −85.3)	<0.001
Interactions				
1000 vs. 600 ppm, *T* = 23 vs. 20°C	−12.9 (−14.4, −9.1)	<0.001	−16.9 (−19.8, −11.8)	<0.001
1000 vs. 600 ppm, *T* = 25 vs. 20°C	−37.0 (−45.0, −27.7)	<0.001	−24.9 (−31.7, −21.7)	<0.001
1800 vs. 600 ppm, *T* = 23 vs. 20°C	−16.3 (−24.3 −13.1)	<0.001	−24.5 (−28.7, −20.6)	<0.001
1800 vs. 600 ppm, *T* = 25 vs. 20°C	−22.8 (−28.6, −17.4)	<0.001	−27.9 (−32.9, −22.9)	<0.001

	DST speed/s		**ALT TAB speed/s**	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
Temperature (°C)				
23 vs. 20	−31.3 (−34.0, −28.7)	<0.001	−32.2 (−33.6, −30.9)	<0.001
25 vs. 20	−74.7 (−82.4, −55.0)	<0.001	−71.4 (−79.7, −63.1)	<0.001

(Continues)

TABLE 5 (Continued)

	DST speed/s		ALT TAB speed/s	
Variable	**β-coeff. (95% CI)**	***p*-value**	**β-coeff. (95% CI)**	***p*-value**
CO_2 level (ppm)				
1000 vs. 600	−28.9 (−31.6, −26.2)	<0.001	−25.3 (−26.7, −24.0)	<0.001
1800 vs. 600	−61.5 (−64.2, −58.9)	<0.001	−55.4 (−56.7, −54.0)	<0.001
Interactions				
1000 vs. 600 ppm, $T = 23$ vs. 20°C	−35.0 (−39.3, −29.8)	<0.001	−19.0 (−21.1, −15.3)	<0.001
1000 vs. 600 ppm, $T = 25$ vs. 20°C	−51.1 (−56.3, −45.7)	<0.001	−36.2 (−40.0, −32.8)	<0.001
1800 vs. 600 ppm, $T = 23$ vs. 20°C	−38.3 (−41.1, −33.6)	<0.001	−34.7 (−37.2, −30.4)	<0.001
1800 vs. 600 ppm, $T = 25$ vs. 20°C	−44.5 (−48.8, −37.2)	<0.001	−43.1 (−48.7, −39.9)	<0.001

Note: 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, 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.

Abbreviations: CI, confidence interval; CPT, Continuous Performance Test; MTS, Match-to-Sample; RL, reversal learning; SDL, Serial Digit Learning; SRT, Simple Reaction Time.

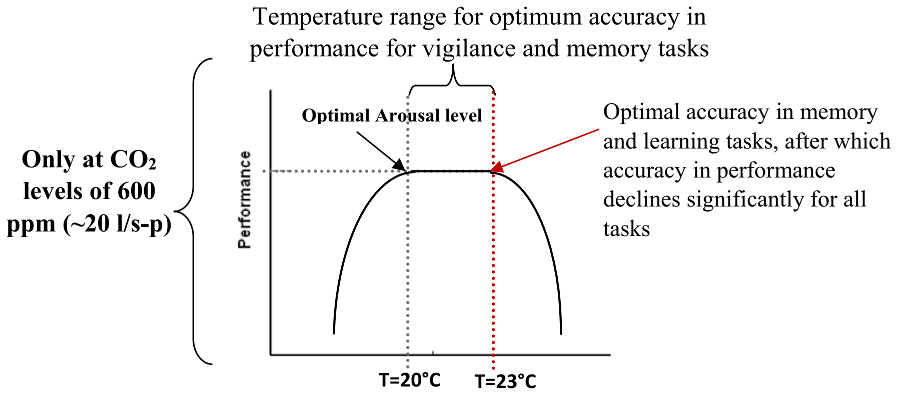

FIGURE 7 Proposed temperature range for optimal arousal and accuracy for memory and learning tasks with reference to the maximal adaptability model (modified from the relation derived by Hancock and Vasmatzidis[25] and Yerkes and Dodson[26])

and Dodson[26]). However, it is important to highlight that temperatures before 20°C needs to be investigated in this climatic context in a similar study for adult female students to check whether this proposed figure of the inverted U-bell shape relationship can be further modified; nevertheless, it was indicated from the survey conducted during phase 1 prior to the pilot study gathering information about the base line conditions in educational buildings in Jeddah, Saudi Arabia, that 20°C is the prevalent temperature set in classrooms and thus this proposed temperature range can be more applicable to real life classroom environments in this context.

This suggestion also agrees well with Seppänen et al.[19] and Seppänen and Fisk.[27] Regarding the speed of response, it was found that the speed significantly increased during the interventions when the temperature was set at 23 and 25°C compared with 20°C, and was sped-up vigorously during IS9 (Temp.: 25°C × CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p); however, this was associated with significantly higher percentage of errors. This finding concurs with Lan et al.[10] who explained that the slower speed at temperature of 20°C can be attributed to the deterioration of dexterity of hands due to stiffening of joints and slow muscular reaction, numbness, and a loss in strength. Discrepancy in results have been reported in other studies, for example, Holland et al.[28] who reported increased task speed as the temperature ascended. However, findings were not consistent in their literature. An interesting pattern of the increase in the speed of performance was observed during the interventions when the temperature was set at 23 and 25°C compared with 20°C and simultaneously the levels of CO_2 were elevated (namely 1800 ppm, ventilation: 2.5–3 L/s-p), significant decrease in the speed of performance was noted, with the effect being significantly stronger when the CO_2 levels were higher (IS9 vs. IS1) that is, (Temp.: 25°C × CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p vs. Temp.: 20°C × CO_2: 600 ppm/ventilation: 20 L/s-p). Bakó-Biró et al.[8] found faster and more accurate responses at higher ventilation rates compared with low rates which explains the lack of focused attention at poor ventilation rates during IS9 (Temp.: 25°C × CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p). The Boxplots in Figures 3–6 indicated that the significant increase in the speed of response was concurrent with a significant increase in the percentages of errors and that the percentage was intensified when temperature increased and ventilation rates decreased (which was a systematic way across all tasks) suggesting the synergetic effect. With reference to the adaptability model and the suggestion made earlier that the temperature range for optimum accuracy in performance for both vigilance and memory tasks could be 20–23°C (only at CO_2 levels of 600 ppm/ventilation: 20 L/s-p); however, when considering the negative effect on the speed at temperature 20°C due to dexterity of hands, this can lead to another suggestion that setting classrooms' temperature at 23°C would be better even if students' optimum arousal was not achieved. This is supported by Yerkes and Dodson[26] who suggested that tasks which demand thinking abilities are better performed under lower arousal state to facilitate concentration, which occurred at 23°C in this study. Nevertheless, this is only proposed at CO_2 levels of 600 ppm (~20 L/s-p), depending on the thermal comfort of occupants which is discussed thoroughly in a separate paper. It is important to highlight these conditions are the same as the prevailing conditions set at the case study building based on the information gathered during phase 1 about the baseline indoor conditions and can imply that the participants were most likely exposed to these favored conditions prior to the interventions and thus possible biased effects on their performances attributed to the pre-set conditions can be excluded. Also, an adaptation period to the interventions' conditions was always provided prior to the cognitive performance assessment to ensure that the effects of the prior interventions' conditions are eliminated.

As mentioned earlier that the significant increase in the speed of response was concurrent with a significant increase in the percentages of errors. Nishihara et al.[29] explained that when the tasks were performed at maximum pace, the subjects made more typing errors. It was reported in the questionnaires that during the interventions when the temperature was high and/or ventilation was poor, over 80% of the participants (25 out of 30 in the pilot study) wanted to leave the room as soon as possible regardless of their performance as they were very uncomfortable during the interventions which they considered least favored, namely IS7, IS8, and IS9, when temperature was set at 25°C (see Section 2.2). Lan et al.[10] explained that when participants felt uncomfortably hot in their study, they tried to complete the tests as soon as possible to escape from the environment. Therefore, it is equally important to consider the effect of occupants' thermal perception not only absolute temperature. The effects caused by the thermal sensations were among the confounders and thoroughly discussed in a separate paper. Another potential explanation for the high speed observed at 25°C was a rise in internal body temperature, which resulted in an increase in the rate of neural activity and a decrease in perceived time, supported by Kiyatkin[30] and Bruyn.[31] Lan et al.[10] provided a thorough explanation on the speed-accuracy trade-off where the neurobehavioral tests in their laboratory experiment lasted only for 30 min; however, the participants were encouraged to perform trying their best during such a duration 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. They referred to Ramsey and Kwon[32] 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, adding that motivated participants may sustain performance by exerting more effort implying that short-lasting effort without health consequences is better than prolonged exposures where continuous effort compensation can cause fatigue and less motivation.

It is important to highlight the limitations of this study as follows: it was not possible to disentangle the effects of pure CO_2 from ventilation rates. For instance, in the study by Allen et al.[5] pure CO_2 was pumped to the rooms of investigation and was considered as a pollutant, whereas in this study CO_2 was the bio-effluent from the participants in the investigated classrooms and was not considered to be a pollutant but an indicator for the efficiency of ventilation whereas in this study CO_2 was the bio-effluent from the participants where no other pollutants were monitored. Therefore, the implication of this is that it cannot be completely excluded that some of the effects observed at certain CO_2 levels were in fact due to other pollutants. Integrating Volatile Organic Compounds (VOCs) and indoor pollutants in a similar study adopting the same methodology would be recommended. Another limitation is the effect of exposure time of the study which lasted for around 1 h per exposure. In the studies of Wargocki et al.[7] and Bakó-Biró et al.,[8] the exposures lasted for a week but the tests they used were shorter. Therefore, 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. Also, the results of this study cannot be generalized to other climates therefore further studies are needed to examine the causality of the observed relationships, the residual confounding, and whether the results can be generalized to other climates, building types, building envelopes, and ventilation modes. It is also worth highlighting that due to the segregation of female from male students in educational buildings in Saudi Arabia, this can be considered as a bias of the study and thus generalization of results to males will not be possible.

5 | CONCLUSIONS

This study indicates a strong association between indoor temperature and ventilation rates, indicated by CO_2 levels, with cognitive performance in adult female (age 16–23) and also indicates a synergetic effect of both; however, this synergetic effect affects memory and vigilance tasks differently. It also indicates that controlling ventilation rates in order to limit indoor CO_2 levels in classrooms to 600 ppm to achieve ~20 L/s-p compared to CO_2 levels of 1000 ppm: ~7.5–8 L/s-p (ASHREA standards recommendation) significantly improves cognitive performance of young female adults (adjusted by confounding factors). The study also indicates that ventilation rate of ~2.5–3 L/s-p attributed by CO_2 levels of 1800 ppm were associated with a significant increase in the percentage of errors compared to ventilation rates of ~20 L/s-p and ~7.5–8 L/s-p (attributed to CO_2 levels of 1000 and 600 ppm respectively). Also, it was found that the speed significantly increased at higher temperatures and was sped-up vigorously during IS9 (Temp.: 25°C, CO_2: 1800 ppm/ventilation: 2.5–3 L/s-p), however; this was associated with significantly higher percentage of errors suggesting that the speed-accuracy trade-off can be due to participants' lack of motivation under stressful conditions particularly that the majority of participants resigned during the least favored conditions when they felt uncomfortably hot suggesting that it is equally important to consider the effect of occupants' thermal perception not only absolute temperature. The effects caused by the thermal sensations were among the confounders and thoroughly discussed in a separate paper. A temperature range for optimal arousal and accuracy for memory and learning tasks was proposed in the range between 20 and 23°C but only at CO_2 levels of 600 ppm (~20 L/s-p), also depending on the thermal perception of occupants. SBS symptoms were observed during the interventions with poor ventilation rates which were found to be associated with the significantly higher percentages of errors that occurred during these interventions. Nevertheless, these results are relevant for short-term exposures lasting no more than 2 h.

AUTHOR CONTRIBUTIONS

Riham Ahmed: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources, and writing – original and final drafts. **Marcella Ucci:** Supervision and validation. **Dejan Mumovic**: Supervision; validation. **Emmanouil Bagkeris:** Formal analysis; software.

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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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