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Indoor Environment Quality (User Comfort, Health and Behaviour)

The Effect of Indoor Temperature and CO_2 Levels on Cognitive Performance of Adult Females in a University Building in Saudi Arabia

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Abstract

Temperatures and indoor CO2 levels within buildings play a crucial role, not only for energy consumption, but also for occupant performance and particularly cognitive performance regarding all mental activities such as thinking, reasoning, and remembering. Using a multi-variable multilevel approach, the effects of classroom temperature and CO2 levels were estimated on vigilance and memory tasks. The analysis is based on two classrooms' physical environmental measurements data in a university located in Saudi Arabia. Participant votes on standard subjective thermal rating scales were collected from 499 adult female students, which were correlated with relevant environmental parameters such as humidity, radiant temperature, air velocity and self-reported clothing levels. Performance against two neurobehavioral cognitive tests was evaluated. The effects of three temperature levels were investigated. Statistically significant associations were observed between the cognitive test outcomes and the investigated exposure conditions of classrooms' temperature and CO2 concentration levels. The associations remained significant after adjusting for confounding variables.

1. Introduction

Students' ability to sustain attention and concentration are key requirements for achieving high performance. According to a number of studies, classrooms' environmental factors such as temperature and ventilation rates are known to disrupt concentration and attention in educational buildings, and are likely to undermine academic performance [1]. In educational buildings, classroom ventilation has been already recognized as an important determinant of indoor air quality since the beginning of the 20th century; however, studies worldwide up to date showed that classrooms ventilation requirements in educational buildings are not met yet in most buildings. With specific regards to Saudi Arabia, recent evidence was provided based on data collected from 36 schools indicating that classroom ventilation rates in Saudi Arabia do not meet building standards [2]. Consequently, this has led to higher indoor Carbon dioxide (CO_2) concentrations in buildings. High CO_2 levels suggest that there is poor ventilation and movement of air in a space, which could lead to increased concentrations of a variety of irritants.

Moreover, providing sufficient classrooms' ventilation rates alone is not sufficient to provide a good learning environment. Room temperature has been found to influence productivity directly and also indirectly through its impact on prevalence of SBS symptoms or satisfaction with air quality [3]. In addition, according to a number of studies, thermal environment that causes thermal discomfort may affect performance. However, scarce data and very little empirical evidence is currently available from the mechanically ventilated and cooled educational buildings located in the hot climates regions and particularly from the Arabian Gulf Peninsula where energy has become cheap and affordable. It is of a particular importance to investigate the effects in air-conditioned buildings since most air conditioners re-circulate a significant portion of the indoor air to maintain comfort and reduce energy costs associated with heating or cooling outside air. Inhaling the circulated air can cause adverse health problems and respiratory diseases attributed to the airborne pollutants [4]. The central nervous system has also been proposed to be a target organ for the detrimental effects of airborne pollutants [5]. In addition, females' educational buildings are presumed to be relatively in a poorer condition and left behind in Saudi Arabia relative to males' educational buildings because of cultural issues, and less attention is paid to them [6]. Furthermore, the effects of room temperatures and indoor air quality are mostly provided from studies conducted in educational buildings which are mostly based on schoolwork by children. On-going research is focusing on children performances as they are more vulnerable to effects from environmental hazards. Nonetheless, the science of developmental neuropsychology recognized that more complex thinking executive functions (such as perception of time, abstract understanding of language and selective attention) occur approximately from the age of 9 to 23 years [7].

Therefore, the main objective of this study is to further underpin the science of IAQ and cognitive performance whilst helping to understand the implications for educational buildings' design on the ability of students to learn in the mechanically ventilated and cooled buildings located in hot climates whilst considering the air-conditioners' acclimation effect in this context of study. Continuous performance test (CPT) was selected as a representative of an attention task and match to sample (MTS) was selected as a representative of a working memory task. Attention and working memory are two key requirements for the tasks conducive to learning. In this study, a multi-variable multilevel statistical modelling approach was adopted which took into account of the nested structure of the data whilst adjusting for the confounding variables including thermal comfort sensations, age, physical activity, clothing levels, stress, caffeine intake, sleeping hours, noise levels, air-conditioners' set temperature at home, as well as ethnic background. Only one recent study has adopted multi-variable multilevel statistical modelling approach; nevertheless, none of these confounding variables were included in their model and the sample size was much smaller whereby no statistically significant associations have been obtained.

2. Research Methods

2.1. *Protocol of the study*

A female university building located in Jeddah, Saudi Arabia, was selected for the study. Four hundred and ninety nine female subjects were tested under nine different exposure conditions combining temperatures (20°C, 23°C and 25°C) and CO_2 levels (600 ppm, 1000 ppm and 1800 ppm). Participants performed eight different cognitive tests (only two of which are discussed in this paper, namely: continuous performance test (CPT) and match to sample (MTS)). In parallel, the participants evaluated their thermal comfort sensations during the exposures. Within-subjects design was adopted where the same participants were exposed to the same exposure conditions, where exposures took place on the same weekday to avoid any influence of weekday on the within-subject difference between conditions. BARS battery “behavioural assessment and research system” [8] was used for the cognitive performance assessment.

Only temperature and CO_2 concentration levels were the independent variables which were manipulated whilst the other parameters were kept within constant ranges during the exposure conditions (namely: sound levels, lighting intensity, air velocity, and relative humidity). The experiment took place every day from Saturday to Wednesday and was always on the same time of the day where each exposure condition lasted for 5 weeks. Two identical classrooms were selected and were used based on their availability. In addition, both classrooms were located in a central location inside the building, which were not exposed to external heat radiation and thus the effect or radiant temperature was eliminated as well as the effect of sun light. Monitoring of environmental conditions, collection of subjective measurements and evaluating the cognitive performance for the tasks selected for the study all took place simultaneously. Cognitive performance assessment started after around 20 minutes from the time the participants entered the classroom in order to allow them enough time to become acclimatised to the classroom's adjusted exposure conditions.

On a day prior to the first exposure the participants attended a practice session. Participants were instructed to forgo their morning coffee on the days of the experimental exposures, and not to drink sodas, energy drinks, as well as avoiding eating chocolate. Participants were also instructed to avoid intense physical activity for at least 12 hours prior to participation and to have adequate amount of sleep during the nights before participation for not less than 7 hours. No restrictions were made on clothing; participants were allowed to wear their typical cloths during the experimental exposures. The participants were instructed to use the computers that were equipped with the cognitive performance software, as these computers were chosen not to be located directly under the ceiling air-conditioners’ diffusers. The duration of the assessment of the cognitive tasks lasted for around 35 min. The subjective questionnaire responses of the participants were collected during the exposures directly after the participants finished performing the cognitive tasks. In order to overcome the carry-over effect, known as the main disadvantage of the within-subject design, the parameters of the cognitive tasks were modified in terms of the sequence of the appearance of stimuli, their shapes, their corresponding response keys, the sequence of digits, and the patterns in the match to sample task, number of trials, duration of tasks, stimulus durations, and the interval between presentation of sample stimulus and distractors.

2.2. *Experimental conditions*

With regards to indoor temperature, based on a pilot study conducted prior to the intervention seeking information about the base line condition in the case study building, the maximum operative temperature the participants were able to tolerate was 25°C. Furthermore, according to a facility management survey which was conducted prior to the intervention as well seeking information about the most common temperature set in educational buildings in Jeddah-Saudi Arabia, 20ºC was found to the most common temperature set in more than 80% of the surveyed buildings. Therefore, the indoor temperatures set during the conditions of exposures were 20°C, 23°C and 25°C. With regards to CO_2 levels, the air conditioning system used in the case study building is a central system (CAV). The damper of the fresh air damper was shut down through the building management system (BMS). The command of the dampers was put in a manual mode which made the dampers no longer controlled by the BMS and hence they did not open by the BMS when the CO_2 exceeded the adjusted CO_2 set point to let fresh air enter the classrooms. CO_2 levels ~1800 ppm were the maximum achieved and ~600 ppm were the minimum achieved. Therefore, the CO_2 levels set during the exposure conditions were 600, 1000, and 1800 ppm.

2.3. *Measurements*

The measurements were collected continuously from 8:30 AM until 3:00 PM. Air temperature, relative humidity, lighting intensity and noise levels were measured by HOBO data loggers. Air velocity was monitored using Testo Large Vane Anemometer Kit and CO_2 concentrations using Telaire 7001 infra-red gas monitor. The equipment were placed in a central location in the classrooms since the outlets and inlets of the air conditioners are distributed equally in the ceiling. Equipment were placed at the head height of a seated person.

2.4. *Statistical analysis*

The statistical analysis was based on a multi-variable multilevel approach. First, uni-variable multi-level mixed effect models were performed to check for any association between the confounders of this study with the accuracy and speed of performance. Age, ethnicity, physical activity, air-conditioners' set temperatures at home, caffeine intake, sleeping hours, thermal comfort sensations, clothing levels, ambient noise, stress, and any reported symptoms by the participants were the confounders found significantly associated. Accordingly, a multi-variable model was performed which adjusted for the associated confounders. The analysis was performed using STATA software.

3. Results

All measured physical parameters describing the conditions in the monitored classrooms during different exposures are listed in Table 1. According to the subjective responses, 99% of participants slept for more than 7 hours during the nights prior to exposures, nobody had caffeinated drinks within 2 hrs prior to participation, and all participants had breakfast on the same day of participation. No great variation in clothing levels was observed; over 90% wore cloths worth 0.85 clo, only 2% reported dissatisfaction with the ambient noise leading to inability to focus, and nobody reported being stressed due to personal reasons.

Insert Table 1

Insert Figure 1

(a) Thermal sensation votes of the Saudi participants at the different exposure conditions investigated in the study; (b) Thermal sensation votes of the non-Saudi participants at the different exposure conditions investigated in the study.

The results also indicated that there were statistically significant associations between all exposure conditions with ethnicity, thermal comfort sensations, air-conditioner (AC) set temperature at home, and the symptoms of intolerable thermal discomfort that impairs focusing ability and symptoms like headache, fatigue and dizziness with the percentages of errors for both cognitive tasks. The estimated effect sizes are listed in Table 2. For the speed of reaction, significant fast performance was observed at the conditions when temperature was set at 25°C and at 23°C relative to 20°C for both cognitive tasks. Significant slowed performance was observed during the conditions when temperature was set at 20°C relative to 23°C and 25°C. In addition, results indicated that the subjective ratings of the

thermal sensation votes of the participants varied by ethnicity. For the Saudi participants, exposure to temperature 23°C reduced their thermal sensations to slightly warm from cool and/or slightly cool at 20°C, while at 25°C almost all participants perceived the ambient thermal environment as uncomfortable hot. However, the non-Saudi participants perceived the thermal environment as slightly cool and/or neutral at 23°C. Fewer participants reported feeling hot at 25°C relative to the Saudi participants while more participants reported feeling cold, cool and slightly cool at 20°C. According to participants' subjective responses, mean AC temperature set at home by the Saudi participants was lower by 2°C relative to that reported by the non-Saudi participants.

Insert Table 2 *p <0.001

4. Discussion

First, with regards to the discrepancy of participants' thermal sensation votes according to their ethnicity, according to Brager & de Dear [9], human adaptation to the thermal environment and expectations as well as past thermal exposure experience play a crucial role in the thermal comfort sensation. Yamtraipat et al. [10] indicated that acclimatization to using home air-conditioners could affect thermal comfort sensation considerably. In addition, after adding the variable of ethnicity in the final model, Saudi participants had significant lower percentages of errors by ~2% relative to the non-Saudi participants. Previous studies also observed differences between students of different ethnic backgrounds while learning in terms of temperature preference [e.g.:11]. Furthermore, after adding the variable of AC set temperature at home to the uni-variable original model, the percentages of errors decreased significantly by ~1% for each unit increase in temperature in the range between 18°C-24°C. It could be postulated that the physiological expectation and repeated exposures can cause AC acclimatization effect to home temperature, which can affect the accuracy in performance significantly. Results also revealed that the estimated effects of temperature on accuracy varied according to the nature of task; however, exposures to CO_2 levels of 1000 ppm and 1800 ppm significantly deteriorated the accuracy in performance for all tasks relative to 600 ppm. For the attention task (CPT), the percentages of errors increased significantly during all exposure conditions relative to the base line

condition at which the temperature was set at 20°C. For the memory task (MTS), the percentages of errors increased significantly during all exposure conditions relative to the base line condition except during condition 4 at which the temperature was set at 23°C. Lan et al. [12] provided an explanation that different tasks are accomplished by different dominant hemispheres and different brain cortices. After adding thermal comfort sensation votes in the final model, the percentages of errors increased significantly for both tasks when participants perceived the ambient thermal environment as cold, warm and hot. For the attention task, cool and slightly cool thermal sensations attributed to significant lower percentages of errors. This result concurs with the findings of Tham and Willem (2010) [13] that moderate cool exposure can result in higher mental arousal. After adding the variables of the reported symptoms of intolerable thermal discomfort that impairs focusing and other symptoms which impaired the focusing ability like headache, fatigue and dizziness, the percentages of errors increased significantly for both cognitive tasks during all exposure conditions. Zhang et al. [14] indicated that the increase in the intensity of neuro- behavioral symptoms like headache and difficulty in thinking can cause subjects to feel more tired and more sleepy. For the significant fastened performance observed at 23°C and 25°C, Bruyn and Lamoureux [15] provided an explanation for the high speed due to a rise in internal body temperature, which resulted in an increase in the rate of neural activity. The significant slowed performance observed at 20°C could be attributed to the deterioration of dexterity of hands due to stiffening of joints and slow muscular reaction, numbness, and a loss in strength [12].

5. Conclusions

- Decreasing classrooms' temperature from 25°C to 23°C, and also increasing temperature from 20°C to 23°C whilst decreasing CO_2 levels from 1800 ppm and/or 1000 ppm to 600 ppm significantly improved the performance of adult female students in a memory task. Decreasing temperature from 25°C and 23°C to 20°C whilst decreasing CO_2 levels from 1800 ppm and/or 1000 ppm to 600 ppm significantly improved their performance in an attention task.
- Cold, hot and warm sensations can negatively affect mental performance for memory and attention tasks while mild cooling sensation can improve mental alertness.

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Table 1. Measured parameters during the exposure conditions (mean ± SD).

Condition	Air temperature (°C)	CO_2 concentration (ppm)	Relative humidity (%)	Air Velocity (m/s)	Light Intensity (Lux)	Noise Levels (dB(A))
Condition 1	20.0 ± 0.2	600 ± 30	42 ± 3	0.15 ± 0.02	400 ± 50	34 ± 2
Condition 2	20.0 ± 0.2	1000 ± 40	42 ± 3	0.11 ± 0.02	400 ± 50	34 ± 2
Condition 3	20.0 ± 0.2	1800 ± 60	42 ± 3	0.08 ± 0.02	400 ± 50	34 ± 2
Condition 4	23.0 ± 0.2	600 ± 30	40 ± 3	0.13 ± 0.02	400 ± 50	34 ± 2
Condition 5	23.0 ± 0.2	1000 ± 40	40 ± 3	0.10 ± 0.02	400 ± 50	34 ± 2
Condition 6	23.0 ± 0.2	1800 ± 60	40 ± 3	0.07 ± 0.02	400 ± 50	34 ± 2
Condition 7	25.0 ± 0.2	600 ± 30	38 ± 3	0.13 ± 0.02	400 ± 50	34 ± 2
Condition 8	25.0 ± 0.2	1000 ± 40	38 ± 3	0.09 ± 0.02	400 ± 50	34 ± 2
Condition 9	25.0 ± 0.2	1800 ± 60	38 ± 3	0.05 ± 0.02	400 ± 50	34 ± 2

Figure 1

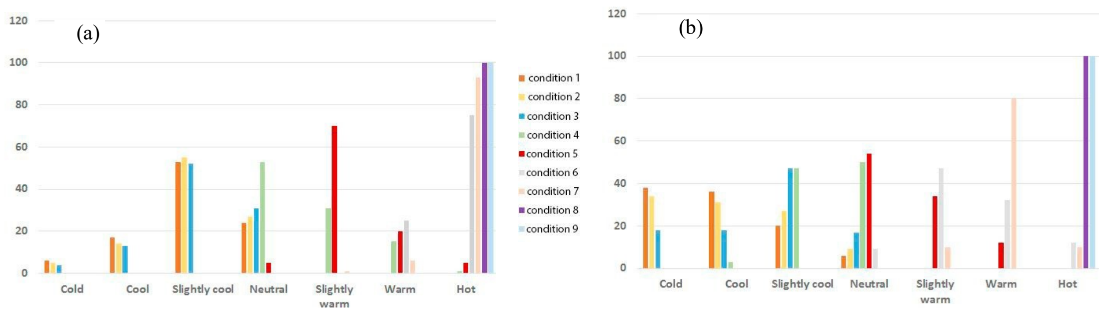

Table 2. Cognitive performance scores at the different exposure conditions investigated in the study.

	Uni-variable model CPT accuracy (error%) estimate (95% CI)	Multi-variable model CPT accuracy (error%) estimate (95% CI)	Uni-variable model MTS accuracy (error%) estimate (95% CI)	Multi-variable model MTS accuracy (error%) estimate (95% CI)
Condition 2 vs. Condition 1	2.74 (1.05, 3.43)*	3.44 (2.03, 4.85)*	2.33 (1.82, 2.85)*	5.26 (4.72, 5.79)*
Condition 3 vs. Condition 1	6.42 (5.05, 7.79)*	7.75 (6.38, 8.12)*	5.87 (5.35, 5.38)*	12.16 (10.18, 14.15)*
Condition 4 vs. Condition 1	4.19 (3.77, 4.60)*	6.53 (5.81, 7.25)*	-1.19 (-1.71, -1.50)*	-5.45 (-6.72, -4.58)*
Condition 5 vs. Condition 1	11.61 (10.20, 12.02)*	15.22 (14.86, 16.59)*	9.95 (9.57, 10.33)*	16.74 (15.80, 17.68)*
Condition 6 vs. Condition 1	14.79 (13.41, 15.17)*	20.56 (19.27, 21.86)*	10.80 (10.28, 11.31)*	21.34 (20.88, 22.81)*
Condition 7 vs. Condition 1	5.96 (4.55, 6.37)*	7.76 (6.67, 8.87) *	7.85 (6.34, 8.37)*	12.16 (11.34, 12.98)*
Condition 8 vs. Condition 1	14.75 (13.34, 15.17)*	20.96 (19.61, 21.30)*	14.42 (13.90, 15.93)*	25.03 (24.53, 26.54)*
Condition 9 vs. Condition 1	22.70 (21.28, 23.11)*	35.08 (34.20, 36.77)*	21.71 (20.34, 22.08)*	32.82 (31.31, 33.33)*
Confounding factors controlled: Ethnicity (Saudi vs. other)	-	-1.63 (-2.30, -0.95)*	-	-1.71 (-2.53, -0.88)*
Thermal Sensation Votes:				

-Cold vs. neutral	-	5.67 (4.10, 6.33)*	-	13.06 (12.19, 14.94)*
-Cool vs. neutral	-	-1.71 (-2.25, -0.17)*	-	-1.09 (-1.46, -0.37)*
-Slightly cool vs. neutral	-	-2.09 (-3.15, -1.03)*	-	-2.47 (-3.44, -1.49)*
-Slightly warm vs. neutral	-	5.22 (4.52, 6.90)*	-	-0.60 (-1.06, -0.21)*
-Warm vs. neutral	-	7.52 (6.01, 8.05)*	-	8.82 (7.33, 9.97)*
-Hot vs. neutral	-	10.90 (9.99, 11.81)*	-	16.06 (15.58, 17.55)*
Temperature at home (per unit increase between 18°C-24°C)	-	-0.80 (-0.97, -0.62)*	-	-1.01 (-1.11,-1.90)*
Reported intolerable thermal discomfort that impairs focusing ability	-	5.06 (4.14, 6.26)*	-	8.06 (7.50, 9.66)*
Other symptoms reported which impaired the focusing ability	-	5.25 (4.22, 6.70)*	-	8.35 7.01, 9.71)*