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Impact of Indoor Temperature and CO_2 Levels on Occupant Thermal Perception and Cognitive Performance of Adult Female Students in Saudi Arabia

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ABSTRACT

Due to hot arid climate in Jeddah, Saudi Arabia, occupants rely on air conditioning (AC) to provide both ventilation requirements and thermal comfort. It is believed that this total reliance on AC have also a significant effect on thermal sensation as well as cognitive performance of building occupants. Using a multi-variable multilevel statistical analysis, the effects of classroom temperature and CO_2 levels on cognitive performance were estimated. Eight neurobehavioral cognitive tests were used to evaluate cognitive performance of 499 female students (16-20 years old). In addition, thermal sensation votes were collected. All participants were exposed to nine different environmental conditions, a combination of three temperature levels 20°C, 23°C and 25°C, and three CO_2 levels: 600 ppm, 1000 ppm and 1800 ppm. The baseline condition levels were set at 20°C and 600 ppm. In this paper the interrelationships between the thermal sensation votes and effects of classroom temperature and CO_2 levels on vigilance (Simple Reaction Test, SRT) and memory tasks (Reversal Learning, RL) are presented. The results suggested that the 'cold' thermal sensations have been linked to significant increase in 'percentage of errors' for both memory and vigilance tasks. Also, the exposure to higher CO_2 levels of 1800 ppm and 1000 ppm have led to a significant increase in the 'percentage of errors' for both cognitive performance tasks compared to the baseline conditions. The study has also confirmed that the significant influence of acclimatization should not be overlooked when setting up the environmental design criteria for buildings in hot arid climates.

KEYWORDS

thermal sensation, temperature, ventilation, cognitive performance, hot arid climate

INTRODUCTION

This study was conducted in Jeddah, which unlike other cities in Saudi Arabia retains its warm climate even in winter. This has consequently led to the total reliance of occupants on air conditioning (AC) for both achieving thermal comfort and providing the prescribed ventilation requirements. Furthermore, due to changing climate an increase in temperature by ~2.5°C is estimated according to regional climate model projections of the average temperature changes (°C) across the Gulf region by 2050 (Alpert et al., 2008). It is also believed that the total reliance on AC for cooling has a significant effect on thermal sensation of buildings' occupants. All these factors have been some of the key drivers of ever increasing energy demand in the Gulf region and a major barrier to adoption of carbon reduction strategies in buildings. For example, it has been shown that only 1°C rise in set AC temperature could significantly reduce energy consumption by ~6% (e.g. Yamtraipat et al., 2005).

Equally important when it comes to design and operation of educational buildings is the consideration of ventilation rates in classrooms and lecture theatres. However, a limited data is available on actual ventilation rates in educational buildings in Saudi Arabia. AlSubaie (2014) provided evidence based on data collected from 36 primary schools, indicating that classroom ventilation rates in educational buildings in Saudi Arabia do not meet the ASHRAE ventilation rates requirements. What might be the impact of lower ventilation rates on cognitive performance of students in hot arid climates is yet to be determined.

Finally, only recently the government in Saudi Arabia, started to promote gender equality to empower women's education and eliminate gender disparity at all levels of education (AlMunajjed, 1997). This has culminated in the last 10 years which has led to the increase in female enrolments at the university level and capital investment in university sector targeting female students. This specific cultural and behavioral context also offers an opportunity to reflect on design of interdisciplinary studies such as this one combining building science and cognitive performance.

METHODS

Only temperature and CO_2 concentration levels (no attempt was made to establish if the CO_2 is a pollutant on its own right) were the independent variables which were investigated in the study whilst the other parameters were kept within constant ranges during the exposure conditions (namely: sound levels, lighting intensity, air velocity, and relative humidity). Based on a pilot study which was conducted prior to the intervention study reported in this paper we obtain some evidence on the base line temperature conditions in the case study building, the maximum operative temperature the participants were able to tolerate was 25°C. Furthermore, according to a facility management questionnaire which was disseminated to the educational buildings in Jeddah, the most common set temperature is 20ºC. Therefore, the indoor temperatures set during the conditions of exposures were 20°C, 23°C and 25°C.

The intervention study was carried out in a teaching room with a CAV AC system with no direct access to sunlight. 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. Therefore, nine different exposure conditions combining temperatures (20°C, 23°C and 25°C) and CO_2 levels (600 ppm, 1000 ppm and 1800 ppm) were investigated in this study (Table 1).

Within-subjects design was adopted where the same participants were exposed to the same exposure conditions. Participants performed eight different cognitive tests (only two of which are discussed in this paper, namely: Simple Reaction test (SRT) as a reference to the vigilance tasks involved and Reversal Learning (RL) is a reference to the memory tasks involved). In parallel, the participants evaluated their thermal comfort sensations during the exposures. The actual mean votes (AMV) were collected. The rating scale used for the thermal sensation vote was based on 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).

Table 1. The exposure conditions investigated in the study.

Conditions of exposure	Ambient temperature	CO2 concentration level	
Condtion 1: Temp: 20°C, CO2: 600 ppm	T1: 20°C	CO2: 600 ppm	Base line condition
Condtion 2: Temp: 20°C, CO2: 1000 ppm	T2: 20°C	CO2: 1000 ppm	
Condtion 3: Temp: 20°C, CO2: 1800 ppm	T3: 20°C	CO2: 1800 ppm	
Condtion 4: Temp: 23°C, CO2: 600 ppm	T1: 23°C	CO2: 600 ppm	
Condtion 5: Temp: 23°C, CO2: 1000 ppm	T2: 23°C	CO2: 1000 ppm	
Condtion 6: Temp: 25°C, CO2: 1800 ppm	T3: 23°C	CO2: 1800 ppm	
Condtion 7: Temp: 25°C, CO2: 600 ppm	T1: 25°C	CO2: 600 ppm	
Condtion 8: Temp: 25°C, CO2: 1000 ppm	T2: 25°C	CO2: 1000 ppm	
Condtion 9: Temp: 25°C, CO2: 1800 ppm	T3: 25°C	CO2: 1800 ppm	

The analysis of data was based on multivariable multilevel analysis approach which takes into consideration the confounding factors' effect including: thermal comfort sensations, age, physical activity, clothing levels, stress, caffeine intake, sleeping hours, noise levels, set air conditioning (AC) temperature at home, as well as the ethnic background and the number of years spent in the country for non-Saudi participants, as well as the detected symptoms related to the inability to focus. Almost no relevant studies have adopted the multilevel modelling approach except for one recent study by Haverinen-Shaughnessy and Shaughnessy (2015), which employed the multilevel modelling approach to find the association between ventilation rates and indoor temperature with mathematics test scores. However, no statistically significant interactions were found because of the limited sample size. The study was designed to have 90–95% power at 95 percent level of significance. Using this information the sample size was calculated using the following formula, (Daniel, 1999):

$$n = \frac{Z^2 P (1- P)}{d^2} \quad (1)$$

Where; n = sample size, Z = statistic for a level of confidence (95% level of confidence used, therefore Z value is 1.96), P = expected prevalence or proportion, and d = precision (In a standard situation, d is considered 0.05 to produce good precision and smaller error of estimate). The calculated sample size was 385. However, the size was over-estimated since the duration of the experiment was long (over one year) and many withdrawals were expected, and particularly in this context of study where research consciousness is absent. Finally, 499 female subjects participated in all nine exposure conditions investigated in the study. The data analysis was carried out in three steps, as follows:

- Step 1: a descriptive analysis was performed to check for any patterns due to intra-individual differences by comparing an individuals' performance pattern of across intervention measures. If all performances fall within the mildly to moderately impaired range, the multilevel mixed effect models can be performed. However, if a significant variability in performances across domains is observed, then a specific pattern of impairment may be indicated.
- Step 2: univariable multilevel mixed effect models were then performed to check whether any association is found between the confounders of this study with the outcomes of interest including: age, ethnicity, physical activity, number of years spent in Saudi Arabia (for non-Saudis), trend of use and temperature of AC used at home, the effect of caffeine, sleeping hours, thermal comfort sensation votes, clothing levels, the effect of ambient noise, and the effect of stress owing to personal reasons not related to the exposure conditions, and/or any

other reported symptoms by the participants which impaired their focusing ability including un-tolerable thermal stress sensation.

- Step 3: multivariable multilevel mixed effect models were applied according to the results of the univariable multilevel mixed effect models, which adjusted for the confounders which were found associated with the accuracy and speed of performance. Two models, one for accuracy (i.e. percentage of error), and the other for speed (i.e. time needed to complete a task) were executed to determine the estimated effect sizes of the exposure conditions relative to the base-line condition (Condition 1) for all the cognitive tasks considered in the study after adding the confounders.

RESULTS

According to the analysis of data, the accuracy (percentages of errors) of the cognitive tasks increased at the different exposure conditions, relative to the baseline condition (Condition 1), after adding the estimated effect sizes of the confounding variables to the zero model and the estimated effect sizes derived from the multivariable multilevel statistical model. The estimated effect sizes are listed in Table 2. For instance, the percentages of errors increased significantly from 2.4% for the SRT test (at the zero model where no confounding variables were added at this stage) to become 5.4% at Condition 2 versus Condition 1 (when CO_2 increased from ranges of 600 ppm to 1000 ppm, while temperature remained constant at 20°C). The increase in the percentage of errors was almost doubled (from 5% to become 9%) at Condition 3 versus Condition 1 (when CO_2 increased from ranges of 600 ppm to 1800 ppm, while temperature remained constant at 20°C), where all reported results were highly significant, $p<0.001$. This trend has continued during all exposure conditions when CO_2 increased from ranges of 600 ppm to 1000 ppm and 1800 ppm, and temperature remained at 20, 23 and 25°C, and particularly when the temperature was set at 25°C. In addition, it is indicated from the Table 2 that significant effects occurred when the variables of ethnicity, number of years spent in the country for the non-Saudi participants, AC temperature set at home in the range between 18 and 24°C, thermal comfort sensations, the reported intolerable thermal discomfort which leads to inability to focus, and other symptoms reported that impaired the focusing ability, were added to the model. By doing simple arithmetic calculations, it was found that the estimated effect size caused by the effects of thermal sensations are the ones responsible for significant amount of the caused effects. With regard to the speed of performance, it was found that the speed of reaction increased significantly during exposure to all the investigated conditions relative to Condition 1.

It is indicated from Table 2 that Saudi participants had significant lower percentages of errors by ~1.5% for the vigilance tasks and ~2.5% for memory and learning tasks relative to the non-Saudis. Also, the inclusion of the confounder of set AC temperature at home in the final model resulted in a significant increase in the percentages of errors for every unit decrease in temperature from 24 to 24°C by an average of ~1%. According to participants' subjective questionnaire responses, the mean AC temperature set by the Saudi participants at home was lower by 2°C, relative to that reported by the non-Saudi participants. An average of ~15% for all tasks was noted for those who reported the symptoms of intolerable thermal discomfort versus which distracted their focusing ability as well as other symptoms like headache, blur eye, heaviness on head for those who did not. With regards to the thermal sensations, it was noted that they account for a considerable amount of the attributed effects. Negative associations for the thermal sensations of cool, slightly cool and slightly warm, relative to neutral, with the percentages of errors for all tasks (higher percentages of errors). However, positive associations with the percentages of errors were observed for perceiving the thermal environment as cold, warm and hot relative to neutral (lower percentages of errors).

Table 2. Changes in percentage of errors for two cognitive performance tasks before and after adding the confounding variables compared to the baseline condition (Condition 1).

The confounding variables considered	Zero model SRT accuracy (error%) estimate (95% CI)	SRT accuracy (error%) estimate (95% CI)	Zero model RL accuracy (error%) estimate (95% CI)	RL accuracy (error%) estimate (95% CI)
Condition 2 vs. 1	2.4 (1.4, 3.4)	5.4 (3.6, 7.1)	3.9 (2.6, 5.4)	7.6 (5.8, 10.4)
Condition 3 vs. 1	5.4(4.9, 6.8)	9.1 (7.5, 11.6)	8.9 (7.6, 9.3)	16.9 (14.6, 19.4)
Condition 4 vs. 1	3.9 (3.5, 4.2)	7.70 (5.9, 9.5)	-1.9 (-2.4, -1.3)	-5.2 (-6.7, -4.7)
Condition 5 vs. 1	9.7 (9.3, 101)	20.6 (15.5, 19.6)	9.7 (9.3, 10.1)	18.1 (15.6, 19.6)
Condition 6 vs. 1	12.1 (11.7, 12.4)	29.1 (26.3, 32.6)	15.1 (14.7, 16.5)	30.8 (27.3, 33.3)
Condition 7 vs. 1	4.4 (3.0, 5.8)	8.4 (6.4, 10.5)	8.8 (8.4, 9.2)	13.9 (11.36, 15.4)
Condition 8 vs. 1	13.9 (13.5, 14.2)	30.3 (27.0, 32.6)	17.3 (16.9, 17.7)	32.4 (29.9, 35.9)
Condition 9 vs. 1	22.1 (21.8, 22.5)	46.1 (43.7, 47.4)	21.6 (20.0, 22.1)	47.6 (43.0, 49.1)
Ethnicity (Saudi vs. other)		-2.2 (-3.4, -1.4)		-2.3 (-3.5, -1.4)
Cold vs. neutral		10.6 (5.1, 7.0)		10.7 (9.1, 11.4)
Cool vs. neutral		-1.5 (-2.2, -0.3)		-0.9 (-1.5, -0.4)
Slightly cool vs. neutral		-2.5 (-3.6, -1.0)		-1.8 (-2.6, -0.1)
Slightly warm vs. neutral		7.0 (4.5, 6.6)		-0.5 (-0.3, -0.8)
Warm vs. neutral		9.1 (5.5, 7.7)		12.2 (7.1, 9.9)
Hot vs. neutral		14.5 (8.3, 10.3)		18.0 (13.0, 15.9)
AC temperature at home (per unit between 18°C-24°C)		-0.9 (-1.1, -0.7)		-0.9 (-1.1, 0.73)
Detected intolerable thermal discomfort vs. not		14.5 (8.3, 10.3)		18.0 (13.0, 15.9)
Other symptoms reported vs. not		16.6 (12.6, 20.8)		17.0 (14.7, 21.8)

DISCUSSIONS

The aforementioned results indicated that the exposure to CO_2 of 1800 ppm and 1000 ppm have led to a significant increase in the percentage of errors for all tasks, versus 600 ppm. These results agree with Twardella et al. (2012) who reported a significant increase in the percentage of errors when CO_2 levels were 2000 ppm, relative to 1000 ppm in their field study, in assessing the effect of IAQ as indicated by the median CO_2 level effect on the concentration performance of students. Also, Allen et al. (2015) observed that several domains of the decision-making tests decreased significantly and by a very high degree during exposure to CO_2 at 945 and 1400 ppm compared with the levels of 550 ppm. It is worth noting that in this present study that CO_2 is not considered to be a pollutant but an indicator of the efficiency of ventilation. In this regard, numerous studies like Bako-Baro et al. (2012) and Coley et al. (2007) provided evidence that poor ventilation rates in classrooms significantly impair students' attention and vigilance. Moreover, interestingly the inclusion of the confounder of set AC temperature at home in the final model resulted in a significant decrease in the percentages of errors for every unit increase in temperature in the range between 18 and 24°C. Correspondingly, it was found that the subjective ratings of the TSVs of the participants varied considerably by ethnicity. For the Saudi participants, exposure to 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 uncomfortably hot. However, the non-Saudi participants perceived the thermal environment as slightly cool and/or neutral at 23°C while more participants reported feeling cold, cool and slightly cool at 20°C. Fewer participants reported feeling hot at 25°C relative to the Saudi participants. According to de-Dear and Brager (1998), human adaptation to the thermal environment, physiological and one's past thermal exposure experience plays a crucial role in human's thermal comfort sensation. Thus, this could be interpreted as the effect of home acclimatization of the most prevailing set AC temperature on mean comfort sensations. It was noted that the thermal sensation votes were very much influenced by the AC set temperature at home. Yamtraipat et al. (2005) supports this suggestion, and indicated that acclimatization to using home ACs could affect thermal comfort sensation considerably.

CONCLUSIONS

- Temperature setting leading to sensation of cold, warm and hot are suggested to be linked to a significant decrease in accuracy for both memory and vigilance tasks, and also the exposure to higher CO_2 levels of 1800 ppm and 1000 ppm compared to 600 ppm.
- It is of a great importance to consider the effects of acclimatization, AC set temperature at home, and the associated intolerable thermal discomfort and other symptoms that may be caused when developing the thermal comfort standards in this climatic context.

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