The Impacts of Indoor Total Volatile Organic Compounds on Cognitive Performance of University Students

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In educational buildings, poor air quality can adversely affect learning and creativity. Existing evidence indicates that high Total Volatile Organic Compounds (TVOC) levels can lead to health issues and reduced cognitive performance. The rising temperatures cause more overheating in buildings. It is crucial to investigate the effects of indoor TVOC levels and temperatures on learning-related cognitive performance in university students.

This project explored the topic through two independent single-blind experiments conducted in a human climate chamber. Experimental Study 1 utilized three TVOC concentrations (100, 1000, and 2000 µg/m³) and involved 33 university students. Experimental Study 2 adopted two temperatures (23°C and 28°C) and two TVOC concentrations (100 and 1000 µg/m³), with 71 university students participating. Cognitive performance was assessed using the BARS cognitive test battery; participants provided their subjective experience of the environment via paper-based questionnaires before and after the experiment.

Result shows only accuracy performance was significantly affected under higher TVOC (2000 µg/m³) and higher temperature (28°C), respectively. The impact of these conditions on reaction speed were inconclusive. The effects of moderate TVOC levels (1000 µg/m³) on both accuracy and reaction speed were also unclear.

Background

Poor IEQ affects teachers and students, negatively impacting teaching effectiveness and students' academic performance [1]. Volatile Organic Compounds (VOCs) are common air pollutants. These compounds are released by building materials, occupants, and various equipment within a building, potentially leading to indoor air quality issues in different areas [2]. Walls and ceilings make up approximately 60% of the total indoor space and are frequently painted [3]. Paints can release amount of VOCs, especially in structures shortly after construction and renovation. Total volatile organic compounds (TVOC) refer to the combined concentrations of both identified and unidentified VOCs.

Climate change is leading to a consistent rise in average temperatures and an increasing frequency of heatwaves worldwide. Highly airtight structures can result in insufficient ventilation, leading to potential overheating and the accumulation of air pollutants [4, 5]. Many studies have highlighted instances of overheating in UK schools [6, 7]. Elevated temperatures can further increase VOC emission rates of building materials, resulting a potential risk to students exposed to both high temperatures and elevated TVOC concentrations.

According to the British standard BS EN 16798-1, a TVOC level below 300 µg/m³ is deemed very low, while a medium level of about 1000 µg/m³ is acceptable [8]. The BS EN 16798-1 also mentions the upper limit for acceptable classroom temperatures during summer as 28°C [8]. Elevating indoor temperatures may lead to productivity losses and the onset of health symptoms [9, 10]. Research on the impact of VOCs on cognitive performance remains inconclusive. Investigation into the combined effects of temperature and VOCs on cognitive performance is even less. Except one early study, no recent studies have delved into this specific area of research [11].

Experimental studies

We conducted two experimental studies to better understand university students' cognitive function and perception during acute exposure to VOCs and elevated temperatures. Both studies were conducted in a controlled, mechanically ventilated climate chamber. The ventilation rate was controlled to 8.3 L/s per person, relative humidity was maintained at 50%. A commercially available solvent-based paint was chosen as the VOC source. The TVOC levels were generated using a paint container assembled from a jar and a lid with an opening. Indoor air was analyzed by the GC-MS system. Tiger PID gas detectors were utilized to enable real-time monitoring. Cognitive performance was assessed through various cognitive tests. We used the Behavioural Assessment and Research System (BARS) as cognitive test, employed ten tasks to assess participants' cognitive performance. Response Speed and Error Rate were the main outputs.

The exposure procedure began with a 20-minute introductory session, followed by a 35-40 minute cognitive test session. Both before and after the cognitive test, a paper-based questionnaire was used to collect perceptions such as thermal sensation and air quality. The questionnaire also collected potential confounders of the cognitive results, such as gender, age. Raised symptoms were collected after the exposure. Univariable multilevel linear regression models were used for data analysis. Participants' perceptions were analysed by ANOVA, followed by pairwise comparisons to explore interaction effects.

The impact of acute indoor TVOC exposures

This study used a 1x3 within-subject single blind design. Three conditions are shown in **Table 1**. The study comprised 33 participants, most of whom were postgraduate students (66.7%), Chinese speakers (84.8%), and 91% were in the age group 20-28 years.

Result shows in eight out of ten tasks, reaction speed was generally higher at elevated TVOC levels. But only the one task demonstrated a significant difference between low levels, 333 (45ms), and medium-high levels, 385 (72ms), p=0.003. Reaction speed increased by 23 ms (7%) when exposed to the medium-low level, and by 52 ms (16%) when exposed to the medium-high level. Therefore, from the univariable model, it cannot be concluded that acute exposure to medium-low or medium-high TVOC levels has a significant effect on reaction speed. **Figure 1** displays the mean error rates for each cognitive task. Eight out of ten tasks showed a numerical increase from low to higher TVOC levels. Univariable regression models indicated significant effects in the following five tasks: MTS, RLT, SAT, SRT, and DST. Across these tasks, the average error rate was 2.7% higher at the medium-low level compared to the low level, and 4.9% higher at the medium-high level than at the low level. Therefore, acute TVOC exposure affects accuracy performance, but the effect is only evident at medium-high TVOC levels.

Table 1. *Conditions of Experimental study 1.*

	VOCs Levels		
	Low	Medium-low	Medium-high
TVOC Concentration	0-300 μg/m³	1000±200 μg/m³	2000±200 μg/m³

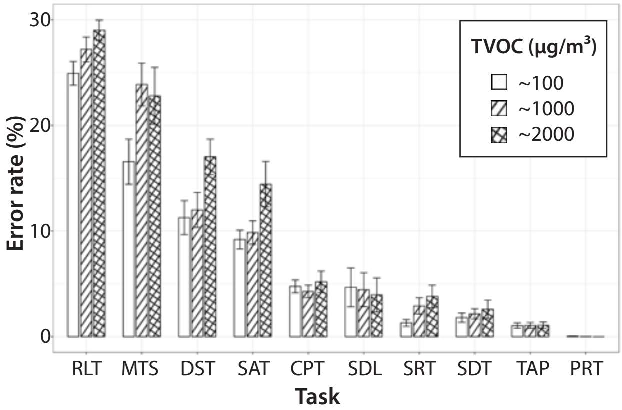

Figure 1. Error rate of each cognitive task under three levels of exposures (mean (SE), n=99).

ANOVA analysis shows for perceived air quality, there was a significant main effect of TVOC level and a significant interaction effect between TVOC level and time. Participants perceived worse air quality at higher TVOC levels. Post-hoc comparisons highlighted that participants were more likely to report "worse air quality" at elevated TVOC levels with increased exposure duration (**Figure 2**).

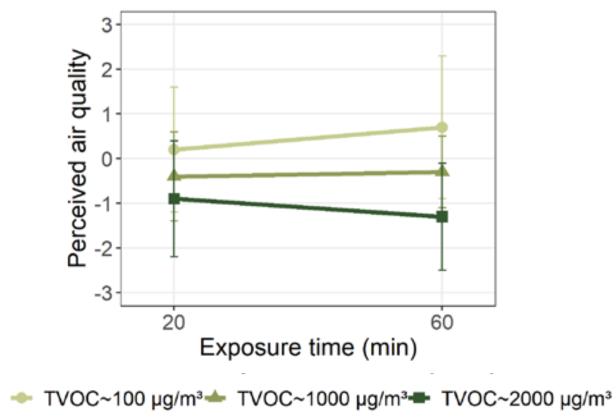

Figure 2. Subjective assessment of perceived air quality (mean (SD), n=99).

After the exposure, there was a marked increase in symptoms reported across all conditions. Participants exposed to higher levels of TVOC were more likely to report symptoms by the end of the experiment. The most commonly reported symptoms included dizziness, fatigue, and eye irritation. Univariable logistic regression analysis showed that eye irritation was significantly associated with medium low TVOC exposure.

The combined impacts of indoor temperature and TVOC

This study utilized a 2x2 within-between participant single-blind design. The temperature served as the within-participant factor, while the TVOC level acted as the between-participant factor (see **Table 2**). The study comprised 71 university students, with 35 participants in the low TVOC group and 36 in the medium-low TVOC group. The majority of participants were postgraduate students (74.6%) and identified as Chinese speakers (83.1%), with 83% of them aged between 20 and 28 years.

For reaction speed, only one task, showed a significant effect, indicating a 46ms (12%) increase in reaction speed at 28°C compared to 23°C. Regarding the impact of TVOC, only two tasks showed significant effects, with an average decrease in reaction speed of 110ms (9%) under medium-low TVOC levels compared to low levels. No significant effects were found between TVOC levels and other tasks. Overall, the reaction speed for most tasks was not significantly associated with either temperature or TVOC levels. **Figure 3** shows the average error rates across all cognitive tasks. A numerical increase in errors was observed at 28°C for most tasks, irrespective of TVOC levels. Five of the ten tasks were significantly impacted by temperature. On average, the task error rates were 3.5% higher at 28°C compared to 23°C. Overall, high temperature significantly impacts accuracy performance, while the impact of TVOC levels was unclear.

The study found a trend that medium-low TVOC levels might enhance the effect of temperature. When using 23°C as the reference category and grouping by

Table 2. *Experiment setting.*

Low TVOC group		Medium-low TVOC group	
TVOC: 0 - 300 µg/m³ Sample size: 35		TVOC: 1000 ± 200 µg/m³ Sample size: 36	
Low temp. 23°C	High temp. 28°C	Low temp. 23°C	High temp. 28°C

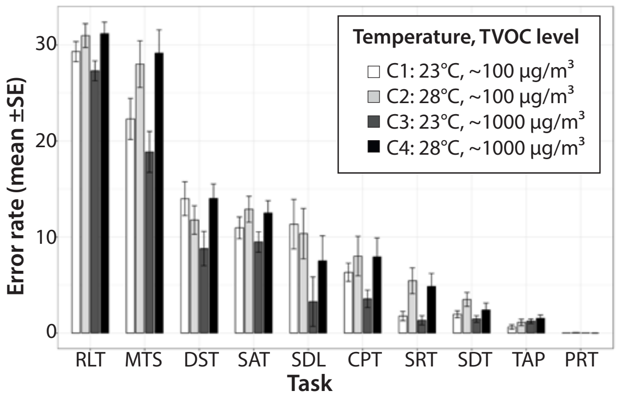

Figure 3. Mean error rate (%) of each cognitive task *in study 2.*

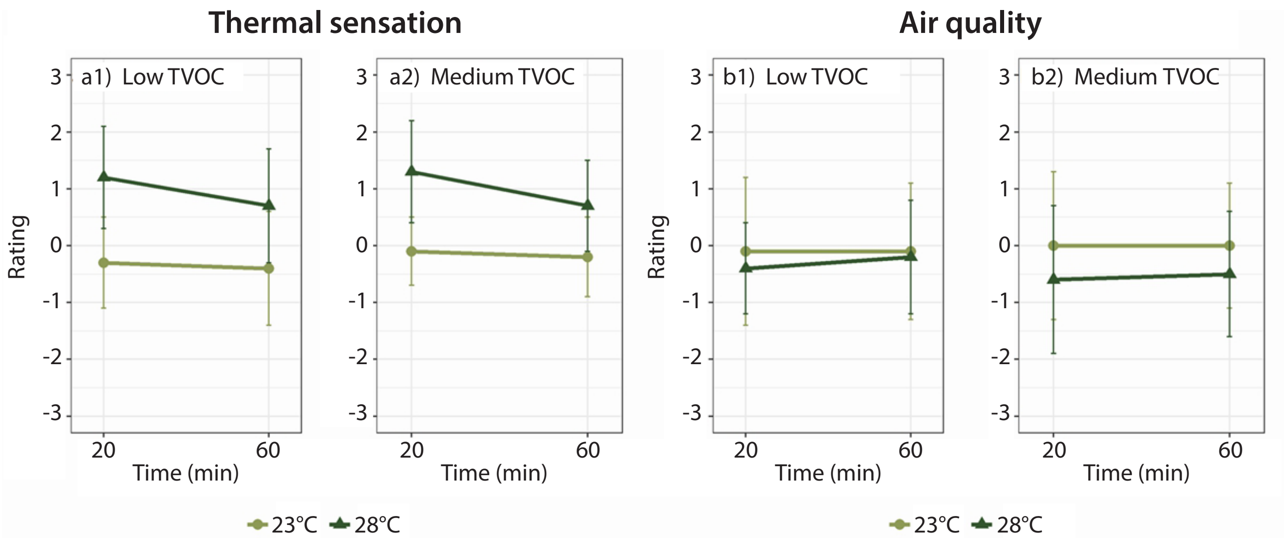

Figure 4. Participant perception average rating at 20 and 60min exposure, mean (SD). Thermal sensation (a, -3 "Extremely cold" to 3 "Extremely hot"); air quality (b, -3 "Extremely bad" to 3 "Extremely good").

TVOC level, an increase in temperature from 23°C to 28°C resulted in an average error increase of 2.4% at the low TVOC level and 5.2% at the medium level. However, the interaction is statistically insignificant. The temperature impact was significant for most tasks at the medium-low TVOC level but not at the low level. Therefore, the interaction effect of temperature and TVOC exposure remains to be validated.

There was a significant interaction effect between temperature and exposure time. Exposed at 28°C resulted in a thermal rating decrease of about 0.5, shifting from "feeling hot" toward "neutral" throughout the exposure period (see **Figure 4a**). Pairwise comparison indicated that such change was significant regardless of TVOC levels, demonstrating a clear instance of thermal adaptation over time at elevated temperatures. The perception of air quality was significantly impacted by temperature variations; participants rated the air quality as "Slightly bad" when exposed at 28°C (see **Figure 4b**). After 60 minutes of exposure, the average increase in participants reporting at least one symptom was 33%. Frequently reported symptoms included eye irritation, fatigue, dizziness, headache, and stuffy nose, with eye irritation being the most frequently reported symptom across all conditions.

Conclusion

2000 μg/m³ TVOC level had a significant effect on accuracy performance. A temperature of 28°C significantly increased error rates on various cognitive tasks among university students, while no conclusive impact on reaction speed was observed. Additionally, no significant interaction effect between temperature and TVOC was observed. Significant impacts were noted in attention, short-term memory, and working memory tasks. Subjective perceptions of air quality worsened at higher TVOC levels, with the highest TVOC exposure triggering the most symptom reports. Commonly reported symptoms after the experiment included eye irritation, fatigue, dizziness, headache and stuffy nose.

The current TVOC standard is generally applicable since cognitive performance is minimally affected at 1000 μg/m³. However, future indoor overheating may occur more frequently, potentially exacerbating the cognitive effects of indoor temperatures, especially in newly built and renovated structures. The higher TVOC exposure may negatively affect memory, wellbeing, and satisfaction with indoor spaces. Therefore, after new construction or renovation, monitoring TVOC levels is crucial. If elevated levels are detected, installing air purifiers with activated carbon filters or enhancing mechanical ventilation can help mitigate these effects.

In addition, future standards may need to classify TVOC limits according to different temperature ranges. Specifically, stricter TVOC limits could be established for higher temperatures. This adjustment becomes particularly important during the summer, as buildings with insufficient ventilation are more likely to experience overheating and elevated TVOC levels simultaneously.

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