Cognitive well-being in classrooms: A holistic investigation into Indoor Environmental Quality in New Zealand primary schools

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Abstract

Children spend about 80-90% of their time indoors, making the quality of indoor environments (IEQ) crucial, particularly since children are more susceptible to pollutants due to their developing bodies and higher relative air intake per body weight. This study examines the influence of various indoor environmental conditions on cognitive performance in primary school students. Data collected over the first three weeks from a total eight-week cognitive study are analysed, focusing on the impact of thermal comfort and CO_2 levels as proxies for ventilation.

Classroom environments were categorised into three conditions: 'TEST 1' (moderate CO_2, temperature, and humidity), 'TEST 2' (elevated CO_2, optimal temperature), and 'TEST 3' (higher CO_2 and temperature). The findings are based on Shapiro-Wilk normality tests, linear regression, ANOVA, and Kruskal-Wallis tests across three cohorts (RM5, RM6, RM7). Results show that 'TEST 1' conditions generally support standard cognitive performance, while 'TEST 3' conditions, characterised by elevated CO_2 and temperature, negatively impact working memory and attention. 'TEST 2' conditions present mixed results, suggesting that even minor changes in environmental factors can influence cognitive outcomes.

Overall, the study highlights the necessity of maintaining optimal indoor environments to support cognitive functions and academic performance. Sensitivity to environmental conditions varies among cohorts, indicating that personalised approaches to environmental management may be required to optimise learning conditions.

Keywords

cognitive performance, thermal comfort, CO_2 levels, ventilation, primary school classroom environment

1 INTRODUCTION

Children spend 80-90% of their time indoors, making the quality of indoor environments (IEQ) crucial for their health and learning. Children are more vulnerable to pollutants as their bodies are still developing and they inhale more air relative to their body weight than adults. Poor indoor conditions can negatively impact children's health and educational outcomes, especially during critical stages of cognitive growth (Salthammer, et al., 2016; Temprano, et al., 2020; Thoua, et al., 2022)

Classroom occupancy and design significantly influence IEQ. Typical classrooms hold 17-30 students in spaces of 40-80 m², providing 2.27-3.63 m² per student. High-density classrooms can compromise air quality, thermal comfort, and noise levels. Effective ventilation and climate control are essential to maintain a healthy learning environment (Hama, et al., 2023; Sadrizadeh, 2022)

Schools often have higher occupant densities than offices, stressing the need for optimal IEQ to support cognitive function and academic performance. The sporadic use of school buildings complicates maintaining stable IEQ, underscoring the need for reliable ventilation and climate control during operational hours to ensure a beneficial learning environment (EPA, 2016).

Overall, maintaining high IEQ in schools is vital for promoting students' cognitive development, academic success, and overall well-being.

2. IMPACT OF IEQ ON ACADEMIC PERFORMANCE AND COGNITIVE FUNCTION

We will explore how thermal comfort and CO2 levels, as proxies for ventilation, impact cognitive development in educational settings. Understanding these key aspects of IEQ is crucial for enhancing students' cognitive functions and academic performance. This examination highlights the need for optimal indoor environments to support cognitive well-being and academic success.

2.1 Thermal comfort

Commonality between the research outputs from Wargocki and Wyon (2013) and Haverinen-Shaughnessy et al. (2015) pointed to the positive correlation between lower classroom temperatures and improved student performance.

Both studies investigate the impact of thermal conditions within the classroom setting on the cognitive performance of children, focusing particularly on the effects of temperature reduction on academic outcomes. Wargocki and Wyon (2013) identified a dose-response relationship indicating that a 1°C drop in classroom temperature could potentially enhance performance speed in arithmetic and language tasks by 4% for 10-12-year-old students.

Similarly, Haverinen-Shaughnessy et al. (2015) examined the influence of classroom temperatures on fifth-grade students' academic performance. Their findings suggest that a reduction in temperature within the 20–25 °C range is associated with significant improvements in mathematics scores, and to a variable extent, in science and reading scores as well.

Jiang's 2018 study in rural Northwest China incorporated adaptive theory by considering the participants' thermal preferences in various temperature conditions ranging from 10 °C to 20 °C. The study acknowledged that occupants could adapt to their environment, indicated by the 12-year-old participants reporting thermal neutrality at 14.5 °C — a temperature that reflects local climatic norms and clothing practices, with an insulation value of 1.55 clo. A notable 80% of the children described a sense of comfort at 14 °C. The adaptive theory is further supported by the observation that attention test accuracy peaked under slightly cool conditions, suggesting that students had adapted to their environment to maintain focus and cognitive function. Although perception and comprehension did not show substantial differences across the temperature spectrum, deduction tasks were most accurately performed in the cooler settings, underlining the adaptability of cognitive functions to preferred thermal conditions.

On the flip side, Fadillah et al. (2020) found through their study in Indonesia that an optimal warmer room temperature around 29 °C enhanced concentration levels, challenging the cooler preferences observed in Jiang's study. This outcome aligns with adaptive theory, which posits that cognitive performance is influenced by individuals adapting to their prevailing thermal environment, which in this case, is the tropical climate of Indonesia. Hence, students performed better at this higher temperature, which was more in line with their acclimatisation and thermal comfort zone. These differing findings between the two studies exemplify the adaptive theory's premise that people's thermal comfort and performance levels are relative to their customary environments, indicating that thermal preferences and their cognitive effects are not universal but context dependent.

2.2 CO_2 as proxy for ventilation

Coley et al. (2007) found a negative correlation between elevated CO_2 levels and the Power of Attention in educational settings. The "Power of Attention" cognitive function refers to an individual's capacity to concentrate on a particular task or piece of information while filtering out distractions and irrelevant information. This cognitive function is critical for learning and processing information effectively, particularly in environments like classrooms where focus and the ability to follow instructions are essential.

As CO_2 concentrations rose from an average of 690 parts per million (ppm) to 2909 ppm, there was approximately a 5% decrease in students' attentiveness. This implies that as the quality of air in the classroom deteriorated due to higher CO_2 levels, students' ability to maintain focus on the teacher's instructions declined. High CO_2 levels in the air can lead to a variety of physiological and cognitive effects, such as drowsiness, lethargy, and a diminished ability to concentrate—factors that are critical to the Power of Attention. When students are less able to pay attention, their cognitive resources are spread thin, and they may find it challenging to stay engaged with the lesson, absorb new information, and perform academically.

Therefore, the study by Coley et al. emphasises the importance of maintaining good IEQ in learning environments to ensure that the Power of Attention in students is not compromised, thereby allowing for optimal learning conditions.

Commonality was found between this study and three others, showing a clear link between better ventilation, which typically corresponds to lower CO_2 levels, and improved cognitive function and academic performance in students.

Haverinen-Shaughnessy et al. (2011) show a quantitative relationship between increased ventilation rates and the success rate of language and mathematics tests, implying that better air quality, which is often reflected by lower CO_2 concentrations, supports cognitive performance. The subsequent study by Haverinen-Shaughnessy et al. (2015) also supports this by showing enhancement in mathematics scores with increased ventilation rates, further substantiating the notion that adequate ventilation is crucial for maintaining cognitive functions that are essential for learning and test-taking. The research by Petersen et al. (2015) added to these findings by demonstrating improvements across various cognitive performance tests when ventilation rates were increased in classrooms.

Collectively, these studies affirm the hypothesis that improved indoor air quality, primarily due to increased ventilation, is associated with better attention, cognitive performance, and academic outcomes. They all point towards the importance of environmental conditions in the learning process, particularly the role that CO_2 levels and ventilation play in affecting students' ability to focus, process information, think critically, and ultimately, succeed academically.

This study has been conducted in accordance with the following standards and guidelines. The World Health Organisation (WHO) recommends maintaining a temperature range of 18°C to 24°C during school hours when classrooms are occupied. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) suggests that the ideal relative humidity (RH) should be between 40% and 60% if the temperature is set within the 18°C to 24°C range. The New Zealand Standard for Ventilation and Air Quality (NZS 4303:1990) specifies that CO_2 levels in indoor environments should remain below 1000 ppm to ensure acceptable air quality. Furthermore, the New Zealand Ministry of Education's 2017 guidelines emphasise the importance of managing indoor air quality (IAQ) and thermal comfort in classrooms, stating that CO_2 levels should be maintained well below 1000 ppm.

Recognising IEQ's pivotal role in education, this research study quantifies cognitive function changes due to variations in thermal comfort and CO_2 levels as a proxy for ventilation. The research design includes continuous monitoring of thermal comfort and CO_2 levels as a proxy for ventilation, and cognitive metrics across multiple classrooms. For this paper, cognitive function is limited to concentration, reasoning and short-term memory.

3. THE NEW ZEALAND CONTEXT

In Auckland, a mild, temperate maritime climate predominates, with average summertime (December to February) daytime temperatures ranging from 20 to 25 °C, and winter (June to August) daytime temperatures spanning from 11 to 15 °C, as reported by NIWA (2023a). Primary school students attend classes from 09:00 to 15:00, Monday through Friday.

According to Swarbrick (2012), the bulk of NZ's school infrastructure was built in the 1950s and 1960s. These structures were intentionally crafted for natural air circulation, consisting of single-story, timber-framed buildings equipped with large, single-glazed windows that could be opened to usher in daylight and airing for ventilation. Notably, these buildings were constructed without insulation, a feature that only became a NZ standard requirement in 1978.

4. RESEARCH METHODOLOGY.

The chosen primary school, built in 1965, is in the temperate climate of North Shore, Auckland, which experiences an average annual temperature of 15.6°C and receives around 1,231 mm of rainfall, according to NIWA's (2023b) report. As depicted in **Figure 1**, the school caters to 160 children between the ages of 5 and 11 in multi-age group classes. The facility includes seven classrooms of equal floor area and a library space. All classrooms are situated on the first floor and feature doors on the North side that open directly to the play area. The classrooms facilitate cross ventilation through windows on both the North (front) and South (back) sides, with louvres installed on the upper section of the north wall that typically remain slightly ajar to enable natural airing. The specific classes involved in this research study are denoted in orange on **Figure 1** and are identified as RM1-RM3 to uphold confidentiality. RM1 is approximately 90 m from the Main Road, which helps to reduce auditory disturbances.

4.1 Ethics protocol

The study was conducted in accordance with the Massey University Human Ethics (High Risk) protocols, as outlined in the approval document SOA 21/53.

4.2 Self-administered online cognitive tests

Creyos, formerly known as Cambridge Brain Sciences (CBS), offers a comprehensive web-enabled platform for cognitive assessments. This platform enables users to self-administer well-validated neuropsychological tests, modified for remote usage as highlighted by Hampshire, Highfield, Parkin & Owen (2012). Each task dynamically adjusts in complexity in reaction to the user's performance, as explained by Thienel, Borne, et al. (2023).

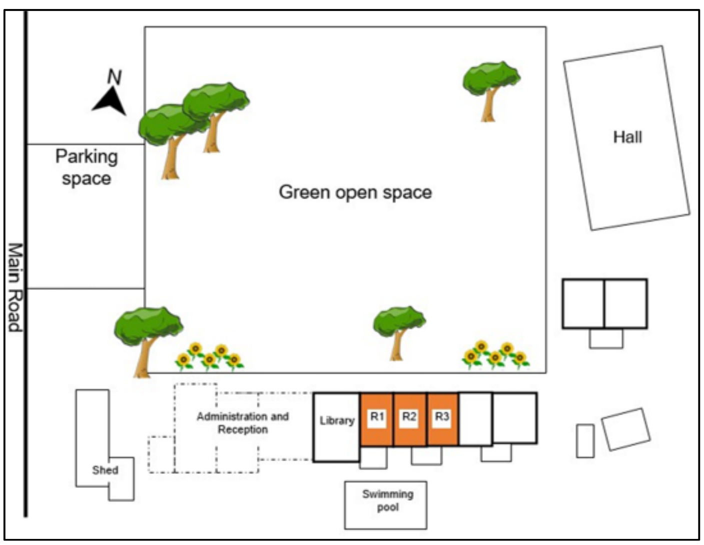


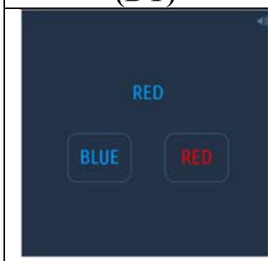
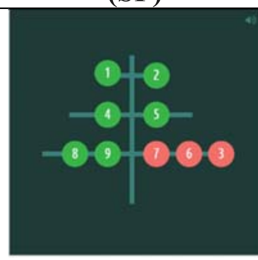
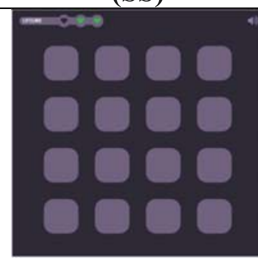
Figure 1: Site Map of School and Location and Study Classrooms

The tests provided by Creyos have undergone rigorous validation across numerous studies, with research cohorts ranging from the healthy population to individuals with medical conditions, as shown in work by Levine et al. (2013), Brenkel et al. (2017), as well Nichols, Wild, Owen & Soddu (2021). Past research has also employed these tests to investigate the cognitive effects of indoor thermal conditions (Ko et al., 2020; Barbic et al., 2019; Luo et al., 2023).

Table 1 provides an overview of the selected four tasks which have been designed to evaluate concentration, reasoning, and short-term memory. The tasks featured include:

- Double Trouble (DT): Evaluates concentration by requiring users to respond to stimuli in situations that challenge their ability to stay focused. Real-life equivalent: Ignoring background conversations while trying to concentrate on a task.
- Spatial Planning (SP): Evaluates the user's ability to develop and execute a plan through specific tasks. Real-life equivalent: Strategically packing items into the trunk of your car to ensure everything fits.
- Spatial Span (SS): Tests short-term memory by asking users to recall spatial sequences. Real-life related activity Following a set of dance moves.
- Odd One Out (OOO): Assesses deductive reasoning by challenging users to identify the item that doesn't belong in a given set. Real-life equivalent: Determining the truth of a situation based on a set of given facts.

Table 1: *Four Neurocognitive Tasks from Creyos*

Double trouble (DT)	**Spatial planning (SP)**	**Spatial span (SS)**	**Odd one out (OOO)**
			

4.3 Test administration and procedure

Prior to the commencement of the testing session, the researcher offered a comprehensive briefing on the tasks ahead. Each task was introduced to the students with the aid of screenshots and verbal instructions tailored to their age group, enhancing the clarity of the on-screen prompts. Students had the option to go through an online tutorial to familiarise themselves with the tasks, after which they engaged with the 'gamified' tests (as depicted in **Figure 2**). The entire sequence of tasks was designed to be completed within a time frame of approximately 15 to 20 minutes.

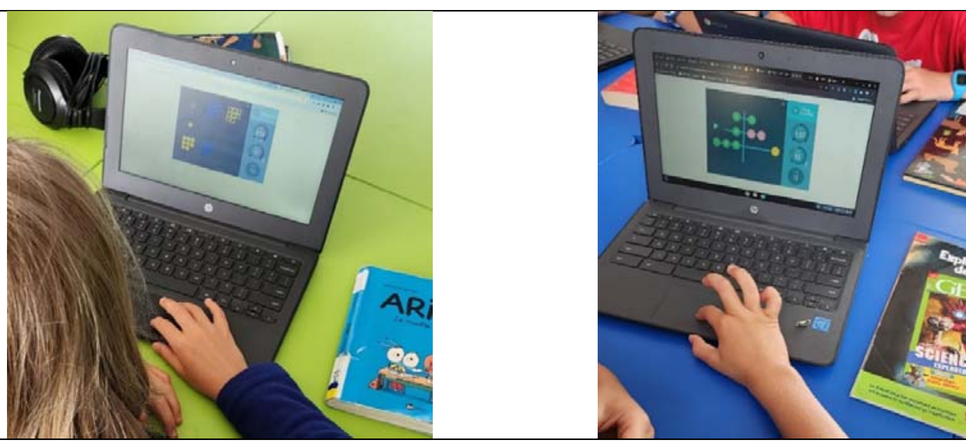


Figure 2: Students Undertaking ‘Gamified’ Online Creyos Tests

In this study aimed at discerning the effects of the classroom environment on student cognitive function, the Principal Investigator avoided prescribing seating arrangements to the students.

Instead, they were advised to select their seats based on personal comfort (as shown in **Figure 3**). Understanding that a natural setting was crucial for the accuracy of the research, the PI chose not to alter the classroom's status quo; thus, the positions of windows and doors remained unchanged for the first two tests. This approach allowed for a more authentic assessment of the environment's impact on cognitive performance.

Figure 3: Students Personal Seating Choices during Cognitive Test

4.4 Internal environmental conditions for the tests

The tests were run under three different environmental conditions.

- 'Test One' hypothesis: The students' cognitive function in a standard classroom setting, without any deliberate modifications to thermal comfort or CO_2 levels, will serve as a baseline measure and reflect typical learning conditions.
- 'Test Two' hypothesis: "Marginally increasing the temperature with a heater while keeping the windows open will have a negligible impact on students' cognitive performance compared to the baseline conditions.
- 'Test Three' hypothesis: Closing windows and doors while continuing to use a heater will affect students' cognitive performance due to altered thermal comfort and CO_2 levels.

5. RESULTS

The data presented in this report is from the first three of twelve weeks of cognitive studies. The size of the population undergoing the cognitive tests exhibits a slight fluctuation over time. This variation can be attributed to occasions when students must depart before the completion of the tests, either to attend additional English for Speakers of Other Languages (ESOL) or Maths testing or because they are summoned to the principal’s office, among other reasons. Such a condition was anticipated and accepted before initiating the testing.

The field study results for examining the three different environmental scenarios were:

- ‘TEST 1’ conditions: Featured CO_2 concentrations around 608 ppm, an ambient temperature of 21.4 °C, and a relative humidity (RH) of 54.2%.
- ‘TEST 2’ scenario: Included CO_2 concentrations close to 707 ppm, with an indoor temperature of 23.3 °C and a RH of 51.5%.

- ‘TEST 3’ scenario: Presented elevated CO_2 levels at roughly 1437 ppm, with the temperature inside at 24.2 °C and a RH of 47.6%.

Table 2 summarises the results of the Shapiro-Wilk normality test conducted on the data obtained from cognitive tests under three different classroom environment conditions each with different levels of thermal comfort and carbon dioxide concentration.

Table 2: *Shaprio-Wilk Normality Test Results for Cognitive Tests Across Different Classroom Environment Conditions*

		SHAPIRO-WILK								
		TEST 1 *p*-value			TEST 2 *p*-value			TEST 3 *p*-value		
	Study size	**RM5**	**RM6**	**RM7**	**RM5**	**RM6**	**RM7**	**RM5**	**RM6**	**RM7**
DT	194	0.1029	0.4567	***0.0087***	0.2067	0.185	0.0555	0.5096	0.7727	0.1068
SP	200	0.973	0.2749	***8.91E-05***	0.7661	0.7829	0.7485	0.9985	0.516	0.187
SS	197	***0.0023***	***0.0002***	***6.86E-05***	0.0502	***0.0003***	0.0614	0.4326	0.0804	***0.013***
OOO	182	0.1107	0.3314	0.564	0.549	0.9421	***3.77E-05***	0.7968	0.5727	0.5436

In synthesising this information, findings suggest that the environment might have differential impacts on cognitive test performance, and these impacts vary depending on both the cognitive domain of the test and the cohort. Furthermore, the sensitivity to environmental conditions, especially noticeable in RM7 across multiple tests and conditions, could be of particular interest and might warrant additional investigation into factors that could explain this cohort's unique responses to the test environments.

Table 3 provides the results from linear regression analyses.

Table 3: Linear Regression Results for Cognitive Test Scores Under Different Classroom Environmental Conditions

	LINEAR MODEL					
	‘TEST 1’		**‘TEST 2’**		**‘TEST 3’**	
	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value
DT	13.429	***2.00E-16***	3.218	0.1739	5.327	0.0315
SP	18.5882	***2.00E-16***	0.9216	0.507	2.1777	0.128
SS	na	na	na	na	na	na
OOO	6.837	***2.00E-16***	-1.5178	0.106	0.3258	0.735

In the ‘TEST 2’ condition, none of the tests (**Table 3**) showed a statistically significant association with the cognitive scores, since all *p*-values exceeded the 0.05 threshold. The DT test had a *p*-value close to the significance cut-off, which may imply a possible, but not statistically confirmed, weak positive relationship. On the contrary, the OOO test exhibited a negative coefficient (-1.5178), which, despite not being statistically significant (*p*-value of 0.106), could suggest that worse performance is associated with the ‘TEST 2’ condition, warranting further investigation.

For the ‘TEST 3’ condition, the DT test showed a statistically significant relationship, albeit the coefficient is smaller (5.327) than in the ‘TEST 1’ condition, which suggests that while there is still a positive effect, it may be weaker. The SP and OOO tests did not demonstrate a statistically significant relationship in this environment, as indicated by *p*-values of 0.128 and 0.735, respectively, which are above the conventional significance level of 0.05.

Overall, the implication of these findings could be that the 'TEST 1' environmental condition is more conducive to better cognitive performance in primary school students compared to the conditions represented by 'TEST 2' and 'TEST 3'.

From **Table 4** ANOVA results for the different cognitive tests and environmental conditions, several deductions can be made:

Table 4: ANOVA Results for Cognitive Test Scores Based on Environmental Type and Room Factor

	ANOVA									
	EnvironType					**RoomFactor**				
	df	**Sum of Squares**	**Mean Square**	**F-value**	***p*-value**	**df**	**Sum of Squares**	**Mean Square**	**F-value**	***p*-value**
DT	2	965	482.3	2.78	0.06	2	2819	1409.3	8.12	0.00041
SP	2	155	77.34	1.23	0.29	2	575	287.68	4.57	0.0115
SS	na	na	na	na	na	na	na	na	na	na
OOO	2	95	47.39	1.78	0.17	2	141	70.74	2.66	0.0729

The DT and SP tests show significant differences in performance across environmental conditions, but not due to room factors. The OOO test does not show significant differences across environmental conditions. This underscores the impact of environmental factors on certain cognitive tasks and suggests areas for further research.

After completing a Kruskal-Wallis test for Spatial Span for Rooms RM5, RM6, and RM7, several inferences can be made:

- The Kruskal-Wallis test for all three rooms indicates no significant differences in cognitive scores across different classroom environment conditions. P-values for RM6 (0.8618), RM5 (0.667), and RM7 (0.4041) all exceed the 0.05 significance threshold.

6. DISCUSSION

Analysing the impact of environmental parameters on cognitive test results within specific conditions raises intriguing discussions. In 'TEST 1' conditions where CO_2, temperature, and humidity levels are moderate, the environment is thought to support standard cognitive performance. However, deviations from this norm in test scores could stem from factors beyond the environment, considering the overall comfort levels should not significantly impair cognitive functions.

On the other hand, the 'TEST 3' scenario, characterised by higher CO_2 levels and increased temperature, presents a contrasting picture. Elevated CO_2 levels have been linked to decreased cognitive functioning, while discomfort from higher temperatures may further impact cognitive performance. Notable deviations from normality, particularly evident in RM7's Spatial Span test under 'TEST 3' conditions ($p = 0.013$), suggest a potential influence on working memory and attention due to environmental stressors. In comparison, the 'TEST 2' scenario, featuring elevated CO_2 levels but optimal temperatures, offers a nuanced perspective. Cognitive performance in this setup is expected to surpass that of the ‘TEST 3’ condition but may slightly trail the levels seen in the normal condition. For example, the significant deviation in RM7's Odd One Out performance ($p = 3.77E-05$) points towards a potential impact on pattern recognition and logical reasoning within this context.

These findings prompt thoughtful discussions on the multifaceted relationship between environmental conditions and cognitive performance. They highlight the intricate interplay between environmental factors and cognitive functions, underscoring the need for comprehensive assessments to better understand the complexities involved in cognitive testing within varying environmental contexts.

Overall, the three different environmental conditions present a range of CO_2 concentrations, temperatures, and humidity levels that can aid in understanding the nuances of how such factors may interact and affect cognitive outcomes in school settings. The subtle differences in cognitive test performance between these conditions, as indicated by the Shapiro-Wilk test results, could suggest that even small environmental changes are impactful.

7. CONCLUSIONS

Therefore, if you were in RM7 and experienced 'TEST 1' conditions, you could expect to maintain standard cognitive performance across most tasks. However, under 'TEST 3' conditions in the same room, you might notice impaired attention and memory, likely due to higher CO_2 levels and increased temperatures. Under 'TEST 2' conditions, you would experience mixed results; although the performance might be better than 'TEST 3' conditions, it still wouldn't be as optimal as in 'TEST 1'.

Similarly, if you were in another room, such as RM5, under 'TEST 1' conditions, your cognitive performance might also be stable. However, elevated CO_2 levels and increased temperatures ('TEST 3') would likely lead to reduced cognitive performance. Like in RM7, a mixed performance would be observed under 'TEST 2' conditions.

The key takeaway is that moderate environmental conditions (like those in 'TEST 1') generally support better cognitive performance. Elevated CO_2 levels and higher temperatures (like in 'TEST 3') tend to negatively impact cognitive functioning. Nevertheless, individual responses can vary, highlighting the importance of considering physical classroom settings, student characteristics, and instructional methods in educational research and practice. Future efforts should aim to optimize classroom conditions to enhance academic performance and cognitive function.

The analyses underscore the complexity of how environmental factors such as CO_2 levels, temperature, and humidity interact to influence cognitive performance. The findings highlight that even small changes in environmental conditions can have measurable effects on cognitive outcomes, although these effects vary depending on the specific cognitive domain and cohort. It does also suggest that other factors, possibly including individual student characteristics or instructional methods, contribute significantly to cognitive performance. Additionally, the specific room in which tests are conducted has a substantial impact on cognitive scores, underscoring the importance of considering physical classroom settings in educational research and practice.

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