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**Impact of Indoor Environmental Quality on Cognitive Function: An
Analysis of Thermal Comfort and Carbon Dioxide Levels in New
Zealand Primary Schools**

*A thesis presented in partial fulfilment of the requirements
for the degree of*

Doctor of Philosophy

in Construction

at Massey University, Auckland, New Zealand

Lara Tookey

2024



**MASSEY
UNIVERSITY**

Declaration of Authorship

I, Lara TOOKEY, declare that this thesis titled, “Impact of Indoor Environmental Quality on Cognitive Function: An Analysis of Thermal Comfort and Carbon Dioxide Levels in New Zealand Primary Schools” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. Except for such quotations, this thesis is entirely my work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work I did jointly with others, I have clarified exactly what others did and what I have contributed myself.

Signed: _____

Date: _____

“Ehara tāku toa, he taki tahi, he toa taki tini.

My success should not be bestowed onto me alone, as it was not individual success but the success of a collective.”

Māori Proverb

Abstract

This study investigates the relationship between indoor environmental quality (IEQ) parameters—specifically thermal comfort and carbon dioxide (CO₂) levels—and the cognitive functioning of primary school students in New Zealand. The research employs a multi-faceted approach, combining field measurements, surveys, and cognitive assessments across multiple geographical regions and seasons. Utilising the SKOMOBO Indoor Environmental Monitoring (IEM) platform and magnetic sensors, the study provides detailed analyses of classroom conditions before and after the COVID-19 pandemic, revealing significant seasonal variations in temperature and ventilation effectiveness.

The research explores factors influencing window-opening behaviours and their impact on IEQ and thermal comfort through questionnaires, observational studies, and sensor data. Additionally, it examines the effects of different environmental conditions on students' concentration, reasoning, and memory, using controlled experiments and the Creyos online cognitive testing platform.

Key findings indicate that optimal thermal comfort and good ventilation significantly enhance cognitive abilities, while elevated CO₂ levels and temperature fluctuations negatively impact performance. The study emphasises the critical role of proper heating, cooling, and ventilation strategies in maintaining a healthy and conducive learning environment.

Based on these insights, the research proposes evidence-based recommendations for improving IEQ in primary schools, including optimising natural ventilation, enhancing insulation and heating systems, and implementing continuous monitoring of classroom conditions. The study highlights the importance of stakeholder involvement in driving systemic changes to create healthier, more effective learning spaces that support students' cognitive development and academic success.

Acknowledgements

I want to start by taking a moment to express my deepest gratitude to my incredible husband. Your unwavering support has been my anchor through every challenge and triumph. Your encouragement, patience, and love have given me the strength to pursue my dreams and confidently face each day. Thank you for being my rock, inspiration, and greatest advocate. I could not have achieved this without you by my side. Your belief in me means more than words can ever express. I am so grateful that I could share this journey with you.

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The list of people I wish to express my gratitude for sharing their knowledge and time is extensive, and I worry about inadvertently leaving someone out. Therefore, I will say: *You know who you are, and I thank you from the bottom of my heart.*

However, I must express my heartfelt thanks to the schools, teachers, and students who participated. Due to ethical considerations, I cannot mention you by name, but please know that this study would not have been possible without your invaluable contributions.

And finally, to my parents, who may not have realised it at the time but who instilled in me a lifelong passion for learning. Thank you for your love, support, and the invaluable gift of curiosity.

I gratefully acknowledge the financial support from the Massey University Vice-Chancellor’s Doctoral Scholarship. This funding has been instrumental in enabling my doctoral research.

List of Abbreviations

ACpH	Air Changes per Hour
AER	Air Exchange Rate
AFFL	Above Finished Floor Level
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning
BRANZ	Building Research Association of New Zealand
CBS	Cambridge Brain Sciences
CO₂	Carbon Dioxide
°C	Celsius
DT	Double Trouble
DQLS	Designing Quality Learning Spaces
EEG	Electroencephalogram
ERH	Equilibrium Relative Humidity
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ICONE	Indice de CONfinement d'air dans Les Ecoles (Stiffness Index)
IEM	Indoor Environmental Monitoring
IEQ	Indoor Environment Quality
ISO	International Organisation for Standardisation
L/s.p	Litres per second per person
m/s	Metres per second
µg/m³	Micrograms per Cubic Metre
MET	Metabolic Equivalent of Task
MoE	Ministry of Education
NIWA	The National Institute of Water and Atmospheric Research
NV	Naturally Ventilated
NZ	New Zealand
NZBC	New Zealand and Building Code
NZS	New Zealand Standard
OOO	Odd One Out

OSH	Occupational Safety and Health
PI	Principal Investigator
PM	Particulate Matter
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPM	Parts Per Million
RH	Relative Humidity
SBS	Sick Building Syndrome
SP	Spatial Plan
SS	Spatial Span
TC	Thermal Comfort
TV&V	Thermal Comfort and Ventilation
UDHR	Universal Declaration of Human Rights
VOC	Volatile Organic Compound
W/m²	Watts per Square Metre
WHO	World Health Organisation

Glossary and Constructs

In this thesis, the subsequent concepts have been embraced.	
Air changes per hour	Air changes per hour indicate how many times, during one hour, the air volume from a room is supplied with outdoor air.
Bio-effluent or Metabolic byproducts	Various pollutants are produced during metabolic processes within the human body. These pollutants generally include CO ₂ , ammonia, hydrocarbons, alcohols, ketones and aldehydes, and their increase in concentration is associated with a decrease in perceived IEQ. In the interest of brevity for this study, ‘CO₂’ will be the default term used unless specified otherwise.
CO₂	Metabolic CO ₂ is a consequence of student density in classrooms and changes to the ventilation rate - generally through airing in New Zealand classrooms as the Ministry of Education prefers natural ventilation. CO₂ will be used as a marker of inadequate ventilation and poor air. This research does not intend to isolate CO₂ from other bio effluents occurring in classrooms, but rather to use it as a ‘proxy for ventilation’.
Cognition	For this study, cognition is <i>limited</i> to the functions of concentration, reasoning and short-term memory.
Indoor Air Quality (IAQ)	IAQ refers to the air quality within and around buildings and structures, that relates to the health and comfort of building occupants (C. Mandin, President of ISIAQ, personal communication, 9 December 2024).
Indoor Environmental Quality (IEQ)	IEQ refers to indoor pollutants (including biological, chemical, or particulate pollutants) and thermal conditions (temperature and humidity), as well as noise, light, and odour.
Steady State CO₂	Represents a balance between CO ₂ production and removal. It occurs when the rate of CO ₂ production from respiration is balanced by the rate of CO ₂ removal through ventilation or air purification. This leads to a constant CO ₂ concentration over time.

Airing and ventilation are key components of IEQ.

Airing is critical in maintaining healthy, comfortable, and productive indoor spaces.

In this thesis, the subsequent concepts have been embraced.

Airing	Renewal of air by opening of windows.
Ventilation	Ventilation is a deliberate design choice that can be natural or mechanical.
	Natural ventilation refers to ventilation designed solely on the effect of wind and the stack effect through dedicated openings (excluding infiltration).
	Mechanical ventilation involves the active supply or extraction of air in indoor environments using powered equipment like motor-driven fans and blowers, commonly integrated into HVAC systems.

List of Papers

Lara Tookey, as the Principal Investigator (PI), served as the primary contributor and lead author for all the conference papers. The PI was responsible for designing and carrying out all the experimental work and analysing the results, with the supervisors providing guidance and assistance in editing the papers. The contribution statements can be found in Appendix A.

Conference papers

- **Tookey, L.,** Boulic, M., Phipps, R., and Wang, Y. (2019). *Air stuffiness index and cognitive performance in primary schools in New Zealand*. Proceedings - Healthy Buildings 2019 Asia and Pacific Rim (HB2019 Asia). Changsha, China: Healthy Buildings 2019 Asia
- **Tookey, L.,** Boulic, M., McDonald, B., Page, W., Wargocki, P., van Heerden. A. (2023). *Ventilation reliability: A pilot study on window opening behaviour in a primary school*. Paper presented at 43rd AIVC – 11th TightVent and 9th Venticool Conference, Copenhagen, Denmark.
- **Tookey, L.,** Boulic, M., Stura, I., Page, W., Wargocki, P., van Heerden. A. (2024). *Cognitive well-being in classrooms: A holistic investigation into Indoor Environmental Quality in New Zealand primary schools*. **Paper pending presentation** at 44th AIVC – 12th TightVent and 10th Venticool Conference, Dublin, Ireland.

Journal papers

- **Tookey, L.,** Boulic, M., Page, W., Wargocki, P., van Heerden. A. (2024). *A Pilot Study on Window Opening Behaviour in Auckland, New Zealand*. *REHVA Journal*. 02: 25-29

Further papers, related to but not directly emerging from the PhD project, has been published concurrently with the work on the PhD project.

- Boulic, M., Wang, Y., Phipps, R., Chitty, C., Cunningham, C., Moses, A., Weyers, R., Jang-Jaccard, J., Olivares, G., Shekar, A., Longley, I., **Tookey, L.**, Ponder-Sutton, A. and the Healthy School Research Team. (2018). *A breath of fresh air: engaging students with air quality science in New Zealand schools*. Paper presented at the INDOOR AIR 2018, the 15th Conference of the International Society of Indoor Air Quality and Climate (ISIAQ), Pennsylvania Convention Center, Philadelphia, Pennsylvania, 22 – 27 July
- Boulic, M., Wang, Y., Phipps, R., Chitty, C., Cunningham, C., Moses, A., Weyers, R., Jang-Jaccard, J., Olivares, G., Shekar, A., Longley, I., **Tookey, L.**, Ponder-Sutton, A. and Waters, D. (2019). *Project: Using a low-cost sensor platform to explore the indoor environment in New Zealand schools*. BRANZ Research Now: Indoor air quality #5

Further research engagement

Further research involvement and dissemination are in chronological order in Appendix B.

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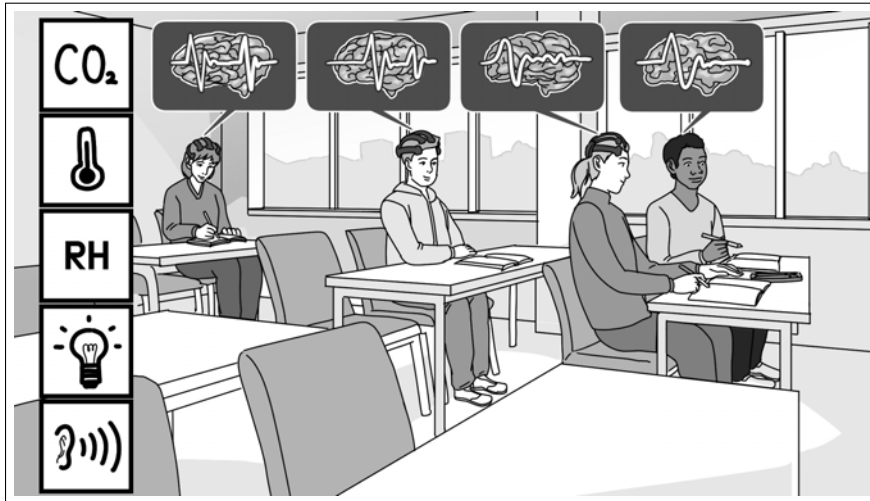
Inception for thesis

This doctoral research project was sparked by an unexpected yet pivotal moment. During a presentation by another doctoral student, the supervising professor, Dr. Boulic, mentioned the possibility of taking on a new student once the current project concluded. In a spontaneous reaction to his query, “Is anyone interested?” my hand shot up. Although initially surprised by my impulsive gesture, I soon realised it stemmed from a desire to expand my research beyond project management.

In subsequent discussions with Dr Boulic, I expressed a growing fascination with the built environment’s influence on its occupants, a topic that intrigued me far more than traditional project management. I aimed not to become an environmental specialist but to explore how indoor conditions impact people’s lives.

Recognising a significant gap in existing research about how indoor environmental factors affect primary school students’ cognitive functioning, my study aims to bridge this gap. My background (both academic and industry) in Quantity Surveying and Construction Project Management, along with Higher and General Education, fueled my drive to explore new research territories. This direction aligned with my conversations with Dr. Boulic, where I articulated my interest in studying the impact of indoor environments on users. To better convey my research idea, I collaborated with an illustrator to develop Figure 1.

FIGURE 1: *Impact of Classroom Environmental Conditions on Cognitive Performance*



Source: Authors Own

Supported by Dr. Boulic and the supervisory team, who acknowledged my industry experience and maturity, I began fieldwork in a Y0/Y1 primary school classroom (4-6 years), focusing on indoor noise levels. Despite three interventions, persistent complaints from teachers about headaches highlighted the adverse effects of environmental factors on well-being, which led to the classroom's repurposing for administrative use. Concurrently, I attempted to study indoor lighting conditions in Y5-Y7 classrooms (9-12 years), but logistical challenges due to frequent furniture rearrangements made this unsustainable.

As my research progressed, I recognised the complex interplay between various environmental factors and expanded my focus to include metabolic CO₂ levels, temperature, and relative humidity. Initially broad in scope, the overwhelming data collection requirements necessitated a more focused analysis to ensure depth and rigour.

Drawing from my educational experiences, where I was steered away from Maths and Science due to perceived limitations, I will assess cognitive functioning instead of academic records to minimise inherent biases. Primary schools were selected as they provide a consistent classroom environment throughout the day, unlike high schools, where frequent room changes could inadvertently improve IAQ through

ventilation.

The objectives of this research are twofold: 1) to develop an understanding of the impact of multiple indoor environmental quality (IEQ) factors on primary school students and 2) to propose actionable insights for improving classroom environments. The research employs a mixed-methods approach by anchoring this study within the intellectual framework of environmental psychology and leveraging guidelines on IEQ. This involves juxtaposing quantitative IEQ measurements with qualitative insights from teachers about window operation and cognitive performance metrics from students.

Aiming to contribute valuable insights to academic literature and practical applications, this study intends to influence educational policies, inform design standards for school buildings, and ultimately enhance learning environments for children.

To achieve a multi-dimensional understanding of cognitive responses to various IEQ conditions, the original study design included electroencephalography (EEG) to visualise participants' brain activity during cognitive tests. EEG technology promises to surpass conventional statistical analysis by directly observing neural activity in response to environmental changes. However, the onset of COVID-19 and the implementation of stringent high-risk ethical guidelines necessitated the temporary shelving of this component. To refine and validate this innovative approach for future studies, I currently explore using EEGs in alternative settings (with adults in portable office spaces and an environmental chamber).

Above all, this research is driven by a personal commitment to enhancing educational experiences for students, ensuring that their learning environments support rather than hinder their cognitive development. From an impulsive hand-raise to a comprehensive research project, this journey exemplifies my dedication to addressing real-world challenges through rigorous, impactful academic inquiry.

Chapter 1

INTRODUCTION

1.1 Research background

This doctoral research initiative is part of a larger Massey University research programme investigating the relationship between thermal comfort and ventilation in primary school classrooms in the unique setting of New Zealand (NZ).

Establishing a solid foundation in the Universal Declaration of Human Rights (UDHR) adopted by NZ on December 10th, 1948, Article 25 of the UDHR emphasises the inalienable right to a decent standard of living for all individuals, underscoring the imperative need for secure, healthy and comfortable indoor environments within educational institutions (UN General Assembly et al., 1948). This holistic approach ensures appropriate ventilation, optimal temperatures... and pollution control to protect the health and well-being of students and staff while supporting children's developmental needs and nurturing a conducive learning environment. By maintaining stringent indoor environmental quality (IEQ) standards in educational establishments, the principles enshrined in Article 25 are honoured, creating a safe and nurturing space where every child, regardless of their background, can thrive and reach their full potential.

The NZ Ministry of Education (MoE) oversees more than 35,000 classrooms in 2,538 schools distributed in six climatic regions (Ministry of Education, 2023). These climate regions are influenced by factors such as latitude, prevailing winds, the surrounding ocean, and the Southern Alps, all contributing to the diverse weather conditions in the elongated geography of the nation (National Institute of Water and Atmospheric Research, 2022). Temperature variations in NZ are significant, with extremes ranging from -9.0 °C to 41.6 °C, accompanied by widely varying

patterns of rainfall (National Institute of Water and Atmospheric Research, 2022). These geographical nuances and climatic variations pose a significant challenge in maintaining suitable educational spaces that adhere to the IEQ standards (Browne and Sameshima, 2012).

The historical background of NZ's school infrastructure built primarily in the 1950s and 1960s (Te Ara - the Encyclopedia of New Zealand, n.d.) **emphasises natural airflow**, characterised by single-story timber-framed buildings with sizable single-glazed windows designed for daylight ingress and natural ventilation. In particular, these structures lacked insulation, a feature that was only mandated as a standard requirement in NZ from 1978 onwards (New Zealand History, n.d.).

The NZ government wants all NZ schools to provide quality learning environments by 2030 ("MOE Te Rautaki Rawa Kura - The School Property Strategy 2030", n.d.). To achieve this, NZ MoE, in partnership with the Building Research Association of NZ (BRANZ), developed the 'Designing Quality Learning Spaces' (DQLS) guidelines (Ministry of Education, 2017).

According to the NZ Post Primary Teachers' Association (PPTA) Health and Safety Guidelines, the temperate ranges for the classroom are deemed acceptable at 19–24 °C in summer and 18–22 °C in winter for passive activities (PPTA - Post Primary Teachers Association, n.d.). The DQLS guidelines stipulate a **minimum** mandatory air temperature of 19 °C (± 1 °C) during hours when the space is occupied, taken at a height of 1.5 m above the finished floor level (AFFL) (Fullbrook et al., 2022). Additionally, the DQLS set a **maximum** temperature threshold, delineating that learning spaces must not exceed 25 °C for more than 80 occupied hours or 28 °C for more than 40 occupied hours. The DQLS guidelines focus on NZ school hours (09:00 to 15:00).

The guidelines of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) (2020) recommend a minimum ventilation rate of 8 litres per second per person (L/s.p) with an assumed maximum occupancy density of 0.5 users/m² (equivalent to 50 people per 100 m² of floor area). This ventilation rate is designed to maintain an average air change per hour (ACpH) of 4, according to the determination of BRANZ 2007 (Ministry of Education, 2017). Before the COVID-19 outbreak, the acceptable CO₂ concentration level in NZ schools

typically stood at 1000 ppm, in alignment with the NZS 4303:1990 standard for “Ventilation for Acceptable Indoor Air Quality” (Standards New Zealand, 1990a). However, the pre-COVID-19 version of DQLS (version 1) recommended that the average CO₂ concentration in occupied spaces could range from 1000 to 1500 ppm (Ministry of Education, 2017). Following the COVID-19 pandemic, this range was revised downward to 800 ppm (Fullbrook et al., 2022). This shift poses a challenge due to the notable reliance of the MoE on natural ventilation methods.

Following New Zealand Building Code (NZBC) Clause G4 ‘Ventilation’ and NZS 4303:1990, it is required that the open window area in classrooms exceeds 5% of the floor area to ensure adequate ventilation (Standards New Zealand, 1990a). However, a survey conducted in 2015 in 40 Auckland primary schools revealed that only 40% of teachers open windows during their teaching sessions in winter (Gully, 2015; Liaw, 2015). This percentage dropped to 15% based on a survey of 33 teachers from nine schools in Christchurch, Dunedin, and Hawke’s Bay (unpublished data). Consequently, in NZ classrooms that rely on natural ventilation, achieving an acceptable ventilation rate can be challenging in winter, even if the school design complies with NZBC requirements.

In NZ, several studies have identified that during winter, primary schools often do not meet the thermal comfort and ventilation (TC&V) guidelines suggested by the World Health Organisation (WHO) and ASHRAE (Bassett and Gibson, 1999; Cutler-Welsh, 2006; McIntosh, 2011). The quality of the learning environment is critical to student health and academic achievement (Chatzidiakou et al., 2015). When the conditions within schools fall below the recommended standards, there is a detrimental impact on children’s health and their ability to perform academically (Bonell et al., 2014; Clarke, 2020; Maccagnan et al., 2019). Given these consequences, it is imperative to develop and implement effective solutions that improve the school environment and ensure a healthy educational environment for children.

As mentioned, the NZ educational landscape faced new challenges during the COVID-19 pandemic, necessitating a recalibration of CO₂ concentration thresholds (800 ppm) to align with global safety guidelines issued by entities such as the Centres for Disease Control and Prevention (CDC) in the United States.

Among the paradigm shifts caused by the pandemic, the importance of adequate

classroom ventilation and monitoring of IEQ parameters came to the forefront. The responses to these challenges included the purchase of 5,000 portable air cleaners by the NZ government for schools to improve IEQ (BEEHIVE, 2022; J. Lee, 2022). Furthermore, the MoE distributed 2,500 Aranet CO₂ monitors to state and state-integrated schools (New Zealand Ministry of Education, 2022), allowing real-time IEQ evaluation and informed decisions on ventilation and occupancy. Integrating these devices allowed for early detection of air quality issues, ensuring a conducive learning environment.

Despite the progress made through these initiatives, challenges persist in ensuring consistent adherence to IEQ standards in NZ classrooms, exemplified by the ongoing variability in teachers' ventilation practices (Gully, 2015; Liaw, 2015). Although the NZ MoE provided schools with guidelines to improve classroom ventilation through effective window management, distributed through posters and presentations, the practical implementation of these guidelines by teachers continues to exhibit inconsistencies.

IEQ significantly affects cognitive performance, learning, and overall well-being. Factors such as air quality (S. Lee and Chang, 2000; Fromme et al., 2008; Wargocki, 2022; X. Zhang et al., 2017), lighting (W. Luo et al., 2023; World Health Organization et al., 1990), acoustics (World Health Organization et al., 1990; Zannin, 2007) and thermal comfort (TC) (Heracleous and Michael, 2019; T. Kramer et al., 2023; Wargocki and Wyon, 2017a) are crucial for shaping cognitive abilities.

Although not incorporating elements such as pollutants, lighting, acoustics, and other characteristics of IEQ into this study, the principal investigator (PI) acknowledges the significant impact and confounding nature of these factors.

Insufficient ventilation and indoor pollutants can hinder cognitive function. Proper ventilation ensures a steady supply of fresh air and reduces pollutant concentrations. Elevated levels of metabolically generated CO₂ have been associated with impaired cognitive function, highlighting the importance of improved ventilation (Bakó-Biró et al., 2007; L. Jia et al., 2021; Jones, 2017; Korsavi et al., 2020).

Exposure to pollutants and unfavourable temperatures can also affect cognitive abilities. Extreme temperatures can impede cognitive performance, attention, and

decision-making. The maintenance of optimal TC contributes to a conducive learning and working environment (de Dear et al., 2013; Heracleous and Michael, 2019; World Health Organization et al., 1990).

In summary, the PI's choice of NZ primary schools as the environment of interest for the thesis is driven by a combination of factors, particularly addressing a gap in the research literature while focussing on a vulnerable population (primary school children). Although research on IEQ's impact on adults in office settings and, to a lesser extent, hospitals, is relatively well-established, the same cannot be said for children in schools. This makes schools a compelling and important environment of interest for the following reasons:

- **Unique vulnerability:** Children are particularly vulnerable to environmental hazards due to their developing physiology and immature immune systems. They also spend a significant portion of their day at school, making the school environment a critical determinant of their overall health and well-being, including cognitive development. This vulnerability requires targeted research in this specific setting (Etzel, 2020; Organization, 2010; Xu et al., 2012).
- **Impact on learning:** Cognitive function is directly related to academic performance. By examining the influence of IEQ on cognitive function in schools, the PI's research can have direct implications for educational policy and practice, potentially leading to improvements in student learning outcomes (J. G. Allen et al., 2016; Mendell and Heath, 2005).
- **Knowledge gap:** Although existing research on office workers and residential settings offers valuable insights, the findings cannot be directly extrapolated to school environments. Children's activities, classroom layouts, ventilation systems, and the specific types of pollutants encountered in schools differ significantly from those in offices or homes. This knowledge gap requires research specifically focused on schools (M.-T. Wang and Degol, 2016; Wargocki et al., 2020).
- **Long-term implications:** The impact of IEQ on children's cognitive development during their formative years could have long-lasting consequences for their overall health and future academic and career success. Studying this impact in schools allows exploration of these long-term implications (Heindel and Vandenberg, 2015).

- **Potential for intervention:** Schools offer a relatively controlled environment where targeted interventions can be implemented and evaluated to improve IEQ (Rupp et al., 2015).

By investigating the interaction between IEQ factors and cognitive function in primary school environments, this study aims to contribute valuable information to the existing body of knowledge, enriching our understanding of how environmental conditions influence student cognitive functioning. In line with the principles of the UDHR and striving for the realisation of quality learning environments conducive to holistic development, this research effort highlights the imperative to prioritise IEQ in educational settings to empower the next generation of learners in NZ.

1.2 The NZ context

This study focusses mainly on Auckland, New Zealand. NZ comprises two main islands: the North Island (34 °S to 41 °S) and the South Island (41 °S to 47 °S), as shown in **Figures** 1.1 and 1.2 (the oval).

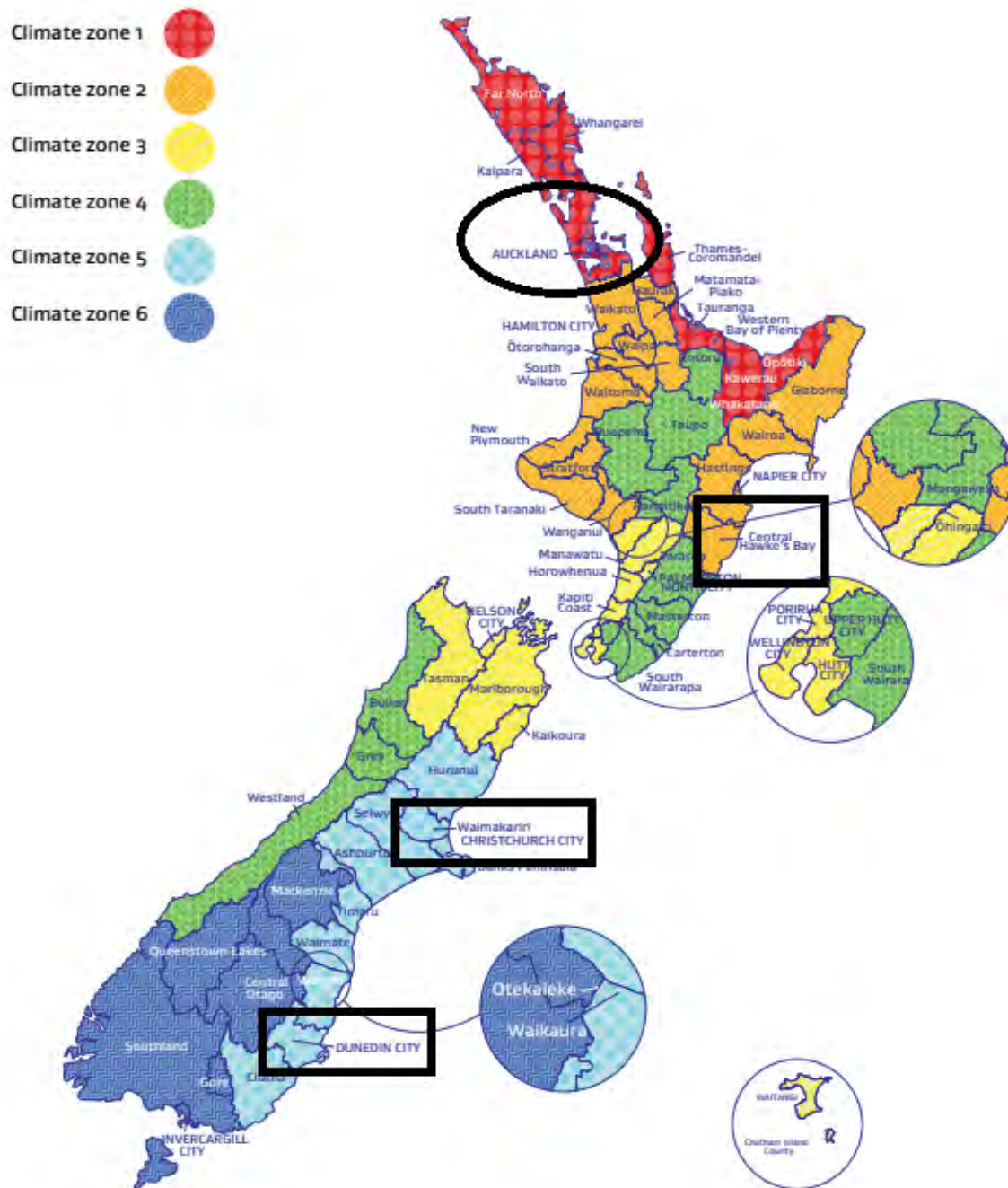
NZ's climate varies from cool temperate in the south to subtropical in the north, with average yearly temperatures ranging from 10 °C to 16 °C according to the National Institute of Water and Atmospheric Research (National Institute of Water and Atmospheric Research, 2022). In the southern hemisphere, the Sun is positioned north at midday, with February typically being the warmest month and July the coldest.

FIGURE 1.1: *Location of NZ within the World*

Source: <https://www.123rf.com/free-images/profile-captain-vector>

The country's climate is divided into six distinct zones, influenced by mountain ranges and prevailing westerly winds (National Institute of Water and Atmospheric Research, 2022). The MoE has further differentiated these zones, as illustrated in **Figure 1.2**.

FIGURE 1.2: *Location of Auckland within NZ*



Source: <https://www.building.govt.nz/>

Note: Weather statistics in this study exclude subantarctic islands and Antarctic territories due to their atypical climate patterns and lack of educational facilities, making the data less relevant for this context.

1.2.1 The Auckland region

The primary school case study in the Auckland region, shown in **Figure 1.2**, is located in NZ's largest city, located at 36.8 ° S. Auckland experiences a mild, temperate maritime climate with average daytime temperatures ranging from 20 to 25 ° C in summer and 11 to 15 ° C in winter, according to NIWA (National Institute of Water and Atmospheric Research, 2022). Due to its isthmus location between the Tasman Sea and the Pacific Ocean, Auckland's wind patterns are influenced by its harbours and hilly topography, resulting in complex local wind conditions. Sea breezes are common in summer, driven by differences in temperature between land and water. Although Auckland's winds are generally moderate, they can be stronger in exposed areas and during specific weather systems like cold fronts. Winter storms from the Tasman Sea can bring gusty conditions, and the region's narrowness can create localised variations in wind speed and direction as winds funnel through certain areas.

1.2.2 The three other regions of interest

Hawkes' Bay, Christchurch, and Dunedin, represented as squares in Figure 1.2, constitute key study regions within this doctoral research. Their inclusion aims to encompass NZ's diverse climatic conditions and urban-provincial distribution. Hawkes Bay is located in the climatic zone 2, while both Christchurch and Dunedin fall within the climatic zone 5. This contrasts with Auckland's location in Zone 1.

1.2.3 NZ primary school classroom profile

Before the 1850s, educational services were primarily supervised by private entities or church organisations. The Education Act of 1877 established the framework for a compulsory and free education system for children aged seven to 13, corresponding to Years 1 through 8. Subsequent adjustments to mandatory age requirements culminated in setting the compulsory school entry age at six in 1964 and raising the official leaving age to 16 in 1989 (Te Ara - the Encyclopedia of New Zealand, n.d.). According to the MoE (2017b), every child within a school's catchment area has the right to enrol and attend their local school, irrespective of the school's capacity.

A detailed examination of the evolving landscape of primary education institutions in NZ and their architectural characteristics, specifically in relation to insulation and

airtightness standards, is provided in Appendix D. This appendix also explores the historical progression of the country's education system from the pre-1850s to the present, offering crucial context for understanding the development of Crown school property in NZ.

The challenges faced by NZ school property management after 2010, including weather tightness issues and earthquake-related damage, have required a re-evaluation of construction practices and materials (Ministry of Education, 2023). Research by Bennett et al. (2019), Boulic et al. (2012), and Bassett and Gibson (1999) indicate common IEQ issues in primary school classrooms in NZ, attributed to architectural design, construction materials, and space management practices. The average age of NZ classrooms, constructed under earlier codes with minimal insulation standards, poses challenges in updating ventilation systems within budget constraints (Bassett and Gibson, 1999; Bennett et al., 2019; Y. Wang, 2020).

As NZ schools navigate these complexities, prioritising natural ventilation methods over costly mechanical systems has become a pragmatic approach to promoting healthy indoor environments conducive to learning (Ministry of Education, 2023).

In 2020, the Ministry released *Te Rautaki Rawa Kura – The School Property Strategy 2030*. This strategy focusses on improving the calibre of NZ's physical and educational settings by achieving the dual objectives of superior learning environments and increased ecological awareness.

This overview outlines the evolution of the portfolio of NZ school properties from pre-1950 to today, highlighting the challenges faced in maintaining and upgrading the ageing infrastructure and the ongoing efforts to improve IEQ and sustainability in educational facilities. Having examined the historical context and current state of NZ's school property portfolio, it is important to investigate the specific challenges related to the insulation and ventilation of these educational facilities.

1.2.4 Challenges related to insulation and ventilation in NZ

Insulation in NZ primary school buildings

The initial mandatory insulation standards for low-rise buildings in NZ were established in 1978. The current insulation standards for residential properties are

outlined in the NZBC under clauses H1 Energy Efficiency and E3 Internal Moisture. The NZS4218 standard, "Thermal Insulation – Housing and Small Buildings," prescribed thermal resistance requirements for insulation in residential buildings. These standards do not specify insulation requirements for school buildings, leading to the application of residential standards in school facilities (New Zealand History, [n.d.](#)).

In 2017, the NZ MoE published the "DQLS: IAQ and Thermal Comfort" guideline to ensure that school environments support education and promote health (Ministry of Education, [2017](#)). This guideline mandates insulation in all new school construction and renovations since January 1st, 2018. Adequate thermal insulation in school buildings, such as roofs, walls, floors, and windows, is essential to maintain indoor temperatures and energy efficiency. Older schools, particularly those built before the 1990s, may lack adequate insulation in walls or ceilings, leading to energy inefficiency. Heat loss in uninsulated classrooms occurs primarily through the roof (40%), followed by walls (30%), windows (20%), and floors (10%). Poorly insulated school buildings can consume significantly more energy to maintain indoor temperatures, which highlights the importance of insulation for energy efficiency.

Although current guidelines require insulation in new school constructions and renovations, older schools can still face energy inefficiency and TC issues due to inadequate insulation. These issues are directly related to the airtightness of school structures, highlighting the importance of addressing insulation and airtightness for optimal thermal performance and energy efficiency.

Airtightness of NZ primary school buildings

A building's energy efficiency is directly influenced by its airtightness, which refers to its resistance to unwanted air movement through cracks and gaps. Although NZBC Clause H1 Energy Efficiency acknowledges the importance of airtightness in new constructions, specific criteria are not outlined.

The research by Bassett ([1999](#)) categorised the NZ houses according to the air changes per hour (ACpH) at 50 Pascal pressure differences. Houses built after 1960 with airtight joinery were considered airtight (5 ACpH), while pre-1960 houses with timber windows were deemed draughty (20 ACpH). Overton et al. ([2020](#)) observed

improved airtightness over time, with ACpH decreasing from 20 for buildings built before the 1960s to 4.5 for structures built from 2000 onwards.

Given the similarities in construction techniques and materials between residential and school buildings of the same era, it is reasonable to apply residential airtightness data to school buildings. Newer school buildings are likely to be more airtight, following the trend of improvements in residential construction.

Although increased airtightness contributes to energy conservation, it can reduce natural ventilation rates, affecting IAQ. Some European countries address this by linking airtightness specifications with mandatory ventilation rates, promoting the principle of "build tight–ventilate right" to balance energy efficiency and IAQ (de Gids et al., 2022).

In summary, this paragraph discusses the importance of airtightness in building construction and its impact on energy efficiency. It highlights that while the NZ Building Code acknowledges the significance of airtightness, it does not provide specific criteria. Research by Bassett (1999) and Overton et al. (2020) shows a trend of improved airtightness in buildings over time, with newer structures generally being more airtight. This improvement is attributed to changes in construction methods and materials. The paragraph also draws parallels between residential and school buildings, suggesting that the newer ones will likely be more airtight. Although increased airtightness contributes to energy conservation, it can also lead to reduced natural ventilation, potentially affecting IAQ. To address this, some European countries have implemented regulations linking airtightness specifications with mandatory ventilation rates, following the principle of "build tight–ventilate right" to balance energy efficiency and air quality.

1.2.5 Summary of the NZ context

This study delves into the educational landscape in Auckland, NZ, located within the diverse climate zones of the country influenced by mountain ranges and dominant winds. The specific focus on the Auckland region reveals its mild, temperate maritime climate characterised by varying temperatures and complex wind patterns. The historical evolution of NZ's education system, from pre-1850s to present-day compulsory education structures, sheds light on the

development of primary schools and their architectural features, notably insulation and airtightness standards. Analysis of primary school numbers and student enrolment over a century highlights fluctuating trends driven by demographic shifts and policy changes. The evolution of Crown school property, categorised into distinct eras, reflects changing construction practices and materials, with a shift towards sustainability and improved learning environments. The challenges of ventilation and insulation in primary school buildings in NZ highlight the importance of airtightness for energy efficiency and IAQ. The research highlights the need to balance energy conservation with adequate ventilation to ensure healthy learning environments, drawing lessons from European practices for optimal building performance.

1.3 Research problem

Existing studies have identified concerning levels of CO₂ and suboptimal temperatures in NZ classrooms, highlighting the importance of a conducive indoor environment for educational outcomes. However, the specific relationship between IEQ elements, such as CO₂ levels, temperature, and ventilation, and their influence on cognitive function, attention span, memory retention, and overall academic achievement among primary school students remains a gap in current research.

1.4 Significance of this study

This research aims to address this gap by examining how variations in IEQ parameters impact student cognitive functioning, specifically looking at concentration, short-term memory, and reasoning. By investigating the correlation between CO₂ levels, TC conditions, and cognitive function, the study aims to uncover the possible effects of indoor environmental factors on students' mental processes.

Understanding the interplay between IEQ and cognitive function in primary school settings is crucial to designing interventions and policy recommendations that promote optimal learning conditions, improve student well-being, and support educational outcomes. By analysing these factors, this research seeks to contribute valuable information on improving IEQ classroom standards and fostering an environment that nurtures student cognitive development and academic progress.

1.5 Thesis outline

The thesis is structured into eight chapters. **Chapter 1** introduces the study, while **Chapter 2** provides a review of the literature. **Chapters 3** and **4** outline the research framework and the methodological process used in the study. **Chapters 5, 6, and 7** detail the results of the three stages of the study, including stage-specific discussions. To ensure clarity, these three chapters are independently presented, each dedicated to a specific aim. **Chapter 8** represents the final section of the dissertation, which delves into the greater importance and consequences of the discoveries made in the earlier chapters. Conclusions, recommendations, and suggestions for future research are presented here.

Chapter 2

LITERATURE REVIEW

This review chapter examines classroom TC, **metabolic CO₂ (as a proxy for ventilation)**, and their impact on cognitive function, along with the effects of natural ventilation (airing) through doors and windows.

In general, the thesis focusses on indoor environmental quality (IEQ), using cognition as a measurement tool rather than the primary focus. Think of it this way: IEQ is the stage, and cognition is the actor's performance. The PI is studying the impact of IEQ, using a tool called cognition instead of academic test results.

2.1 Literature review approach

A systematic search across relevant multidisciplinary databases, including Scopus, Web of Science, PubMed, and Google Scholar. Databases with a focus on the Built Environment, such as ScienceDirect, Taylor & Francis Online, and Emerald Insight, were used. ProQuest Dissertations & Theses Global and other sources of Grey literature (which include government reports, conference proceedings, and technical reports) were also used.

The search was conducted using keywords including combinations of "Child*", "thermal comfort", "ventilat*", "iaq", "ieq", "cognit* perform*", and "Class*", along with additional terms such as "cognition" and "function". The search strategy aimed to identify studies that examine the relationship between IEQ factors (specifically thermal comfort and CO₂ levels) and cognitive performance in school-age children within the NZ context. Relevant studies were selected according to title, abstract and full text, with inclusion criteria focused on peer-reviewed publications reporting quantitative data. The selected studies were then critically assessed and synthesised

to identify key findings and gaps in existing research.

To further enhance the depth of the literature review, the reference lists of the most relevant papers were reviewed to identify additional studies that may not have appeared in the initial searches. This backward citation tracking allowed the PI to discover seminal works and other relevant research that contributed significantly to the understanding of the topic.

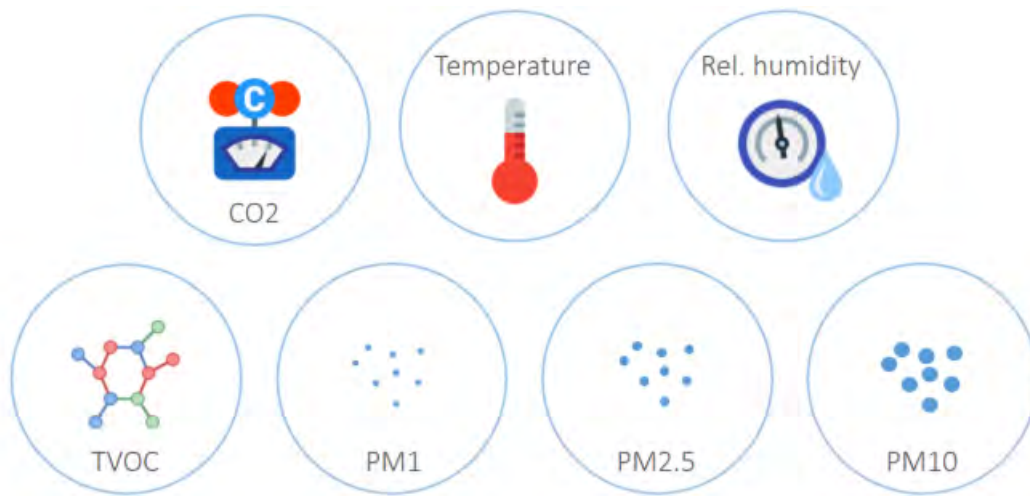
2.2 Introduction and definition of IEQ

Research by Bozzola (2024), Toyinbo (2023), and UNICEF (2019) indicates that children typically spend approximately 80% to 90% of their time indoors, including their residences, educational institutions, and various other indoor spaces.

IEQ is a comprehensive term defined by the US Green Building Council as the aggregation of atmospheric conditions within a building, encompassing factors such as air quality, lighting, TC and ergonomics, all of which significantly impact the experiences and health of the building occupants (US Green Building Council, 2023). This definition is adopted for this study.

Beyond simple comfort, IEQ is a benchmark that measures the holistic healthiness of interior space, covering aspects such as indoor air quality (IAQ), adequate thermal conditions, effective lighting, and sound levels. The Building Research Establishment emphasises the importance of IEQ, underscoring how inferior IEQ can lead to adverse health outcomes, diminish the quality of work productivity, hinder learning in educational contexts, and inhibit patient recovery in medical facilities (BRE, 2023).

The quality of air in the building environment is characterised by a significant variability of physical, chemical, and microbiological parameters (Basińska et al., 2019) as identified in **Figure 2.1**. Indoor air pollution sources in school classrooms, including classroom furnishings, volatile organic compounds (VOCs), and poorly maintained ventilation systems, can affect the IEQ of the classroom. Outdoor pollutants such as traffic, construction, and combustion activities can also contribute to IEQ in a school classroom (Singh, 1996; Wark and Warner, 1981).

FIGURE 2.1: *Potential Contributing Sources to Indoor Air Pollution*

Source: Authors Own

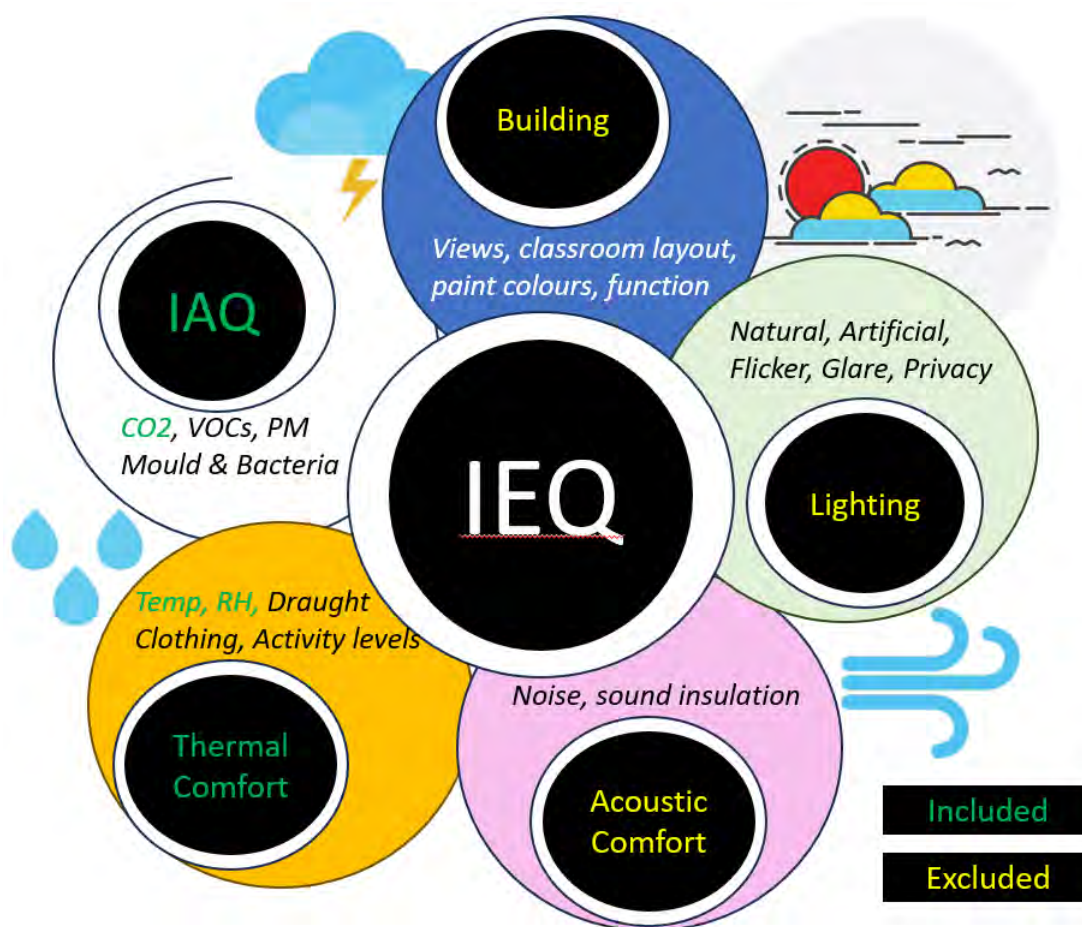
Poor IEQ can worsen or trigger health problems such as asthma, allergies, and respiratory problems, which can be particularly concerning for children due to their developmental stage and higher breathing rates relative to adults (Jones, 2017; Lepeule et al., 2012; World Health Organization et al., 2010). Thus, the emphasis on IEQ and the significant duration that children spend indoors arises from concerns about potential exposure to various indoor air pollutants. The fresher the air, the lower or less significant **Figure 2.1** variables will be if outside air is not polluted.

Various critical aspects, including air quality, access to natural light and views, acoustic conditions, occupant control over lighting and TC, and functional aspects of space, influence the overall quality of the indoor environment. Research emphasises the importance of these factors, as highlighted by Hui (2008), Pietraru (2022), and others. Additionally, Hui (2008) and Mansouri (2022) emphasise that macro-environmental factors such as climate and weather conditions also impact IEQ, illustrated in **Figure 2.2**. The structure and envelope of the building, including the foundations, floors, walls, roof, building services, materials, and the heating, ventilation, and air conditioning (HVAC) systems, further shapes the IEQ, as indicated by Levin (2010). In addition, decisions made by clients and end users about furniture, appliances, and cleaning practices influence IEQ, as noted by Hui (2008) and Seppänen (2004). The complexity of assessing IEQ is compounded by factors such as student health and perceptions, reflecting the various expectations

and susceptibilities of students and teachers, as highlighted by Hui (2008).

The PI decided to expand the definition to include paint colours, classroom layout, and views and other factors introduced by the end user (the teacher and students) to acknowledge the significant impact these elements have on the psychological and physiological well-being of the students, including 'Building' in **Figure 2.2**.

FIGURE 2.2: *Interconnections of IEQ*



Source: Authors Own

By including these factors in the definition of IEQ, although outside the scope of this study, the PI can acknowledge the holistic nature of the indoor environment and its impact on students' overall well-being. This broader understanding can lead to more thoughtful design choices that prioritise student health, comfort, and productivity. Although these elements may be harder to quantify than traditional IEQ factors, their impact is undeniable and deserves consideration in future indoor environment

studies.

The PI is cognisant that myriad elements can influence IEQ within the setting of a primary school classroom, ranging from auditory distractions to the quality of lighting and from the aesthetics of interior decor to the presence of the artwork.

Although traditional definitions of IEQ often focus on measurable factors like air quality, TC, lighting, and acoustics, expanding the definition to include paint colours and views acknowledges the significant impact these elements have on students' psychological and physiological well-being.

Different colours evoke various emotional and behavioural responses (Bluyssen et al., 2020; Krawczyk and Dębska, 2022; Sun and Firzan, 2024). Warm colours like red and yellow can be stimulating and energetic, but can also be potentially overstimulating for some children. Cool colours like blue and green are generally calming and associated with focus and concentration. Neutral colours such as beige and grey can create a sense of stability but can be perceived as dull if not balanced with other colours (Bluyssen et al., 2020; Krawczyk and Dębska, 2022; Sun and Firzan, 2024).

Views of nature, even limited ones, have been shown to reduce stress, improve mood, and enhance cognitive function (Kapoor et al., 2021). Access to natural light and views can also regulate circadian rhythms, promoting better sleep and overall well-being (Westwood et al., 2023). Views can influence the perceived size and layout of a space. A view that extends beyond the confines of a room can make it feel larger and less claustrophobic (Huang et al., 2020).

It is important to note that an exhaustive discussion of these diverse factors is beyond the scope of this study. **The study will focus on TC and CO₂** as indicated by the green text in **Figure 2.2**. The rationale for this limitation is also outlined in the Inception for thesis.

In the context of schools, optimising IEQ is crucial for several interrelated reasons.

1. **Health and well-being:** Healthy indoor environments are essential for the well-being of students and staff. Good air quality, appropriate lighting, and comfortable thermal conditions help maintain good health and reduce the risk of respiratory problems and other health problems (Jones, 2017; Kephelopoulou et al., 2014; United States - Environmental Protection Agency - Indoor Air Division, 1991). Proper maintenance of ventilation systems, building materials, and HVAC systems is critical to ensuring IEQ and a safe learning environment.
2. **Learning performance:** The indoor environment significantly affects students' academic performance and concentration levels. Access to natural light, comfortable temperatures, and appropriate acoustics create a conducive learning environment that supports cognitive function and productivity (Bakó-Biró et al., 2007; X. Zhang et al., 2017; Mistry, 2023).
3. **Comfort and productivity:** A comfortable and pleasant indoor environment can enhance student motivation and productivity. Adequate control over lighting, thermal conditions, and acoustics creates a more enjoyable space for learning (Auliciems, Szokolay, et al., 1997; X. Jia et al., 2024). The selection and maintenance of proper furnishings, appliances, and cleaning practices create a more inviting atmosphere (Fromme et al., 2008).
4. **Satisfaction and retention:** A well-designed indoor environment that prioritises the IEQ factors can lead to higher satisfaction among students, teachers, and staff. This contributes to positive school experiences, higher retention rates, and improved general morale (Ganesh et al., 2021; Levin, 2010; Knez and Thorsson, 2006). Understanding and addressing the diverse needs and vulnerabilities of students is essential to promote well-being and satisfaction.

By addressing and optimising these aspects of IEQ, educational institutions can create healthier, more stimulating, and more comfortable environments that support the well-being and academic success of students and staff.

An issue of concern is when buildings are more *air tight*, resulting from more modern building techniques and materials, this can lead to the accumulation of pollutants that generate poor IAQ (Almeida et al., 2017).

2.2.1 Definition of thermal comfort

ASHRAE 55 defines TC as “*that condition of mind that expresses satisfaction with the thermal environment and is evaluated by subjective evaluation*” (ASHRAE, 2020). This definition is adopted for this study.

Today, the concept of comfort is multifaceted, rendering a concise definition elusive and arguably superfluous. Rybczynski (1986), in his "Onion Theory of Comfort," portrays comfort as an amalgamation of various layers, emphasising the collective significance rather than just the outermost element. However, Rybczynski, in the context of the "Onion Theory of Comfort," does not provide a unique definition of "thermal." Instead, his approach influences how we should think about TC in architectural and environmental terms. In discussing TC as it relates to architecture and environmental design, Rybczynski would refer to the balance of heat gained and lost by the human body and the control strategies used to achieve comfort, such as clothing, building insulation, natural ventilation or the positioning of the building. Rybczynski's "Onion Theory" suggests a layered approach to managing TC, where "thermal" refers to the heat-related aspects of our environmental and personal comfort. So, while Rybczynski may not have redefined the word 'thermal', he certainly reframed the approach to achieve TC in buildings, encouraging an adaptive layered strategy similar to how one could layer clothing to achieve personal comfort in varying outdoor conditions (Rybczynski, 1986).

Before widespread adoption of air conditioning technology, the concept of thermal contentment was not encapsulated by the term "comfort." This term has evolved from its Latin root 'confortāre,' which means 'to strengthen greatly.' The 11th edition of Merriam-Webster's Collegiate Dictionary (Merriam-Webster, n.d.) outlines several interpretations of comfort: the first implies *support* or *assistance*. The second conveys *relief* or *encouragement*. The third denotes a *state of satisfaction* or *satisfaction* derived from a pleasant experience.

2.2.2 Summary of IEQ definitions: A focus on thermal comfort and CO₂

TC is a dynamic and nuanced concept encompassing various aspects of our interactions with our immediate and extended environment, and adapting to these interactions is as crucial as controlling the thermal environment itself (ASHRAE, 2013; Fanger, 1970).

Transitioning from the specifics of TC to the broader concept of IEQ, it is essential to take a step back and look historically at how perceptions and research in IEQ have evolved. Historical scrutiny illuminates a varied past, from initial considerations in industrial settings to advanced, sustainability-driven questions of the present day. This progression reflects technological advances and a deeper appreciation of health and ecological concerns within building design. This narrative shapes our current understanding and future direction in optimising indoor environments.

2.3 Historical perspective on IEQ research

The scholarly inquiry into IEQ originates from the increasing recognition of the relationship between human health and the conditions of the built environment. Early investigations focused on how the internal dynamics of organisations could impact inhabitants' health and well-being. It is crucial to differentiate between IAQ, which focusses on IAQ, and IEQ, which includes factors such as illumination, acoustics, TC, and ergonomic design, which includes, but is not limited to, air quality (Fanger, 2006; Levin, 2010).

The historical trajectory of IEQ research dates back to the systematic examination of ventilation, TC, and illumination and their impact on human health and well-being. This academic journey reflects a shift from an initial concern for health and safety in indoor environments to a more comprehensive perspective that considers the comfort, functional efficiency, and psychological well-being of the occupants. This transition signifies a move from a one-dimensional approach to assessing IEQ.

Several significant advancements and contributors have distinguished themselves within the research domain. Tables 2.1; 2.2; 2.3 and 2.4 provide a summary that highlights key participants and significant events.

TABLE 2.1: Summary of Highlights

Time	Event	Building Type and Parameter	Ref
1818-1901	Max von Pettenkofer - Established permissible CO ₂ concentrations within indoor spaces to measure air quality.	General and IAQ	Sedgwick, 1905
1850	George Derby - Ventilation in schoolhouses needed improvement. This led to various improvements in the architectural designs of school buildings, including higher ceilings, larger windows, and the inclusion of mechanical ventilation systems in some cases.	Schools and IAQ	Rosenkrantz, 1972
1859	"Notes on Nursing: What It Is, and What It Is Not" by Florence Nightingale significantly impacted IEQ through its principles and recommendations for managing patient surroundings for better health outcomes. While not directly labelled under the modern term of IEQ, Nightingale's work discussed several components essential to today's understanding of it.	Hospitals and IEQ	Medeiros et al., 2015
1859	ASHRAE Standard 62 , first published in 1973, regularly updated, crucial document guiding ventilation for acceptable IAQ.	General and IAQ	Persily, 2015
Late 1800s - early 1900s	The School Hygiene Movement - the importance of good hygiene and proper environmental conditions - examined the impact of lighting, classroom size, and air quality on the health and performance of students.	Schools and IEQ	Baker, 2012

TABLE 2.2: Summary of Highlights Continued

Time	Event	Building Type and Parameter	Ref
Early 20th Century			
Early 1900s	Industrial Hygiene Movement	Factories and mines and IAQ	Plog et al., 1996
1910	Lawrence J. Henderson focused on physiological regulation, which had implications for understanding indoor air control and the human body's response.	General and IAQ	Sellers, 1994
Early 1900s	Alice Hamilton - mother of occupational medicine, researched the health impacts of industrial work and the importance of air quality in work environments.	General and IAQ	Sellers, 2007
Mid 20th Century			
	HVAC Developments: The modern evolution of heating, ventilation, and air conditioning systems became a central theme in creating comfortable indoor environments, which led to various studies assessing how these systems impact IEQ.	General and IEQ	Niza et al., 2023; Heracleous and Michael, 2019
1950s-1960s	WHO Air Quality Research - study the effects of air pollution on human health, including investigations into indoor environments. These studies extended to include comfort aspects such as thermal conditions and the psychological implications of space.	General and TC	World Health Organization et al., 1990
1960s and 1970s	Fanger - development of the PMV model	General and TC	Fanger, 1970

TABLE 2.3: Summary of Highlights Continued

Time	Event	Building Type and Parameter	Ref
Late 20th Century			
Established in 1970	EPA - conducted and funded numerous studies on IAQ.	General and IAQ	Wu et al., 2007
1970	The Clean Air Act - primarily aimed at outdoor air pollution, also set the stage for considering the impacts of air quality on health more broadly, indirectly influencing IAQ research.	General and IAQ	Rogers, 1990
1970	Energy Crisis of the 1970s : The energy crisis led to tighter building constructions to save energy, inadvertently resulting in "sick building syndrome" due to reduced ventilation.	General and IEQ	Thörn, 1999
1970s and 1980s	Sick Building Syndrome Research led to further studies investigating various IEQ factors, including IAQ contaminants, ventilation rates, and psychological factors.	General and IEQ	Thörn, 1999
1974–1979	The Harvard Six Cities Study - While primarily focused on outdoor air pollution, this landmark study by the Harvard School of Public Health also had implications for understanding the health impacts of air pollution in general, which overlaps with IAQ concerns.	General and IAQ	Lepeule et al., 2012
1978	The 1st International IAQ Conference , convened by ASHRAE. A group of ten researchers from Denmark, Slovakia, Sweden, and the United States came together to scrutinize research about indoor environments.	General and IAQ	Fanger and Valbjørn, 1979; Andersen, 1985

TABLE 2.4: *Summary of Highlights Continued*

Time	Event	Building Type and Parameter	Ref
1981	ASHRAE Standard 62 - One of the first standards to provide guidelines on minimum ventilation rates for indoor spaces to ensure health and comfort.	General and IEQ	Persily, 2015
1987	The first edition of Air Quality Guidelines for Europe - published by WHO Regional Office for Europe. Updated in 2010.	General and IAQ	Krzyzanowski, 2008
1991	Building Air Quality - A Guide for Building Owners and Facility Managers became an influential source of information on diagnosing and preventing IAQ problems in commercial buildings.	General and IAQ	United States - Environmental Protection Agency - Indoor Air Division, 1991
21st Century			
2010	The WHO Guidelines for IAQ: Selected Pollutants: One of the various reports pivotal in synthesising research findings and providing evidence-based guidelines for making indoor air safe.	General and IAQ	World Health Organization et al., 2010
2019+	Most recently, the global COVID-19 pandemic prompted urgent research into how various aspects of IEQ, particularly ventilation and filtration, affect disease transmission in indoor settings.	General and IEQ	

The early efforts laid the foundation for understanding IEQ and IAQ, emphasising the importance of managing indoor environments to enhance human health, satisfaction, and performance. Building practices evolved with the introduction of new materials and chemical products, increasing the complexity of maintaining

IEQ and IAQ. Concerns about sick building syndrome (SBS) in the late 20th century, marked by symptoms such as headaches, dizziness, and eye and throat irritation, prompted detailed studies on the impact of building design and operation on occupant health.

The shift towards synthetic building materials and tighter building envelopes to improve energy efficiency inadvertently led to the accumulation of indoor air contaminants due to inadequate ventilation and the release of VOCs from new materials and furnishings (Shiva Nagendra and Chithra, 2020; Wilkins et al., 2007). This indoor air pollution spurred further investigations into the association between these contaminants and adverse health outcomes (Davis et al., 2016; Hess-Kosa, 2018; Rosenkrantz, 1972; World Health Organization et al., 2010).

The broader concept of IEQ gained momentum, acknowledging that it encompasses more than just air quality, including TC, lighting, and acoustics, which are vital for occupants' well-being and productivity (Barbic et al., 2022; Toyinbo, 2023; Wargocki and Wyon, 2017a). Governments and international organisations have developed regulations and guidelines to safeguard occupants, recognising the critical importance of indoor environmental parameters. Technological advances in air sampling, environmental sensors, and building automation systems have provided tools for more precise monitoring and management of indoor environments (Kapsalaki, 2017; Niza et al., 2023; United States - Environmental Protection Agency - Indoor Air Division, 1991).

Interdisciplinary academic research expands the understanding of IEQ, delving into topics from the microbiome of the built environment to the psychological effects of indoor spaces on behaviour (Nielsen et al., 2004; Wall, 2016; Wigö and Knez, 2005). In the 21st century, sustainable design and green building practices inform further research agendas. Green buildings strive to minimise environmental impact while improving human health through low-emission materials, natural ventilation, and ecological principles, balancing immediate impacts of the occupants with long-term environmental consequences (Bruhwiler et al., 2021; Diaz et al., 2021; US Green Building Council, 2023).

2.3.1 Summary of historical perspectives

In summary, the foundational research in IEQ has significantly influenced regulatory building codes, occupational standards, and design practices, leading to improved health and efficiency within indoor spaces. As research methodologies advance and our understanding deepens with respect to the interaction between humans and their environments, IEQ research continues to broaden in scope and impact. This evolution drives innovations in building design, enhancement, and management, all designed to promote the well-being of the occupants of the building.

Understanding the interplay between TC&V is key to achieving 'Breathe Easy.' Elevated CO₂ concentrations, often a by-product of inadequate ventilation, can decrease cognitive function and productivity while compromising TC by contributing to a stuffier indoor climate. In contrast, strategies to improve TC, such as temperature control and increased airflow, can affect CO₂ levels by diluting indoor air pollutants and facilitating a healthier breathing environment. This relationship highlights the importance of integrated approaches in the design and management of buildings that simultaneously address TC and air quality to ensure that air promotes physical well-being and mental acuity.

2.4 Breathe easy: Understanding our air quality

Our air is susceptible to composition, temperature, humidity, and quality changes. The sensitivity of the air we breathe to changes can be exacerbated in a classroom setting due to various factors unique to educational environments.

1. **The classroom context** In classrooms, high occupancy often results in increased CO₂ and exhaled gases, which can be exacerbated by inadequate ventilation. This lack of proper ventilation leads to the build-up of pollutants, allergens, and excess moisture, resulting in stagnant air and higher concentrations of contaminants (Zapata-Lancaster et al., 2023; D. Zhang et al., 2022).
2. **Composition:** Air is primarily composed of nitrogen (78%) and oxygen (21%), with trace amounts of gases like CO₂, argon, and water vapour. Any significant changes in the concentrations of these gases can impact air quality and, consequently, human health and the environment (UCAR Center for Science

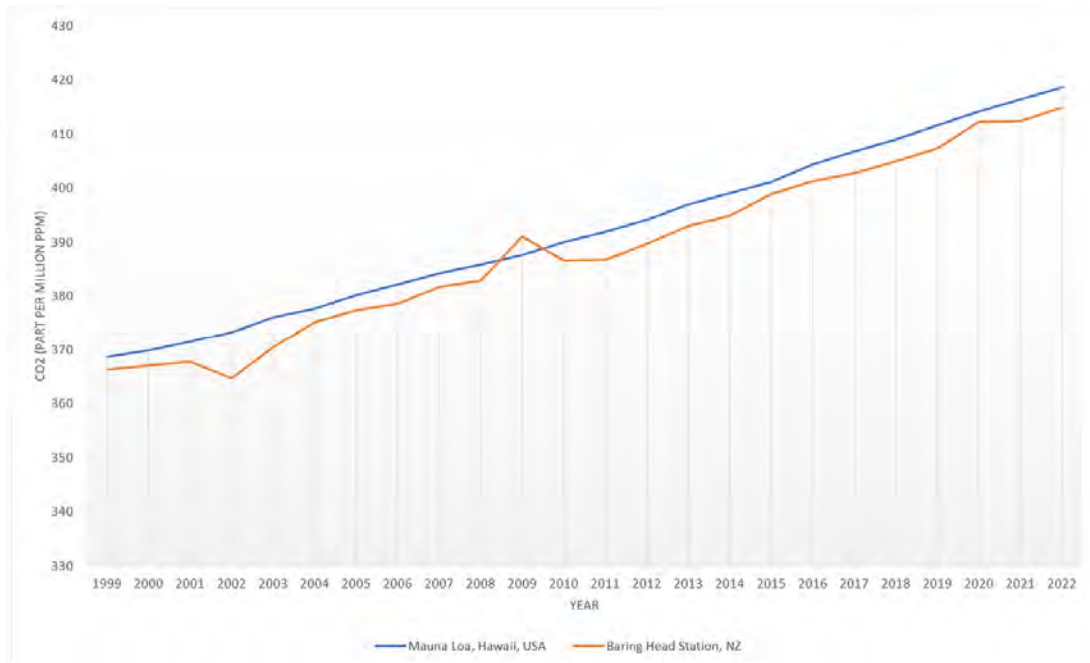
Education, n.d.). As we breathe, we inhale oxygen (O_2) and exhale CO_2 . By comparing the composition of our breath, **Table 2.5**, we can see that we do not fully expel all the oxygen, and the CO_2 level has increased proportionally (Voigt and Pelikan, 2010). When CO_2 is exhaled, it is quickly mixed with the surrounding air, and if the ventilation is suitable, the concentration of CO_2 is reduced rapidly to lower levels (Voigt and Pelikan, 2010).

TABLE 2.5: Composition of our Breath

Inhaled		Exhaled
20.96%	Oxygen (O_2)	Approx. 16%
78%	Nitrogen (N_2)	78%
0.04%	Carbon Dioxide (CO_2)	Approx. 4%
1%	Inert gases	1%

- CO_2 concentration is typically measured in *parts per million* (ppm). While outdoor ambient CO_2 concentrations are generally around 400 ppm, as indicated in **Figure 2.3**, maintaining CO_2 levels below 1,000 ppm indoors is recommended for optimal IEQ (Ministry of Education, 2023; Thoua et al., 2022).
- **Figure 2.3** portrays the ambient CO_2 readings from 1999-2022 (last date data available) (Lan et al., 2023) for both Mauna Loa (northern hemisphere) and Baring Head in NZ (southern hemisphere) stations. Both stations are part of the Global Atmosphere Watch (GAW) program of the World Meteorological Organization (National Oceanic and Atmospheric Administration, 2023).

FIGURE 2.3: *Ambient CO₂ Readings from Baring Head and Mauna Loa Stations 1999 - 2022 (adapted from Lan et al., 2023)*



Source: <https://gml.noaa.gov/>

3. **Indoor pollutants and high activity levels:** Classrooms may harbour indoor pollutants from poor cleaning practices, off-gassing of building materials, cleaning agents, and allergens like dust and mould. Active tasks like movement, projects, and group discussions can disturb these pollutants, impacting air quality and occupant well-being (Hess-Kosa, 2018; World Health Organization et al., 2010; Telejko and Zender-Świercz, 2017).
4. **Temperature and humidity control:** Inadequate temperature regulation and humidity levels in classrooms can cause discomfort and affect air quality. Improper heating or cooling, coupled with incorrect humidity levels, can promote mould growth, dust mites, and allergens, impacting comfort and health (Wargocki et al., 2019; O'Lenick et al., 2019; Toftum et al., 1998).
5. **Shared spaces and educational materials:** Shared classrooms accommodating diverse activities heighten the risk of cross-contamination, germ transmission, and accumulating pollutants from various origins. Moreover, items like art supplies, science experiments, and cleaning products may release VOCs and other substances, potentially compromising IAQ (Zapata-Lancaster et al., 2023).

6. **General pollutants and allergens:** Airborne pollutants from industrial processes, vehicle exhausts, and diverse sources deteriorate air quality, posing risks to respiratory health. Minimal levels of particulate matter, sulphur dioxide, nitrogen oxides, and VOCs can have detrimental effects. Furthermore, airborne allergens such as pollen, dust mites, pet dander, and mould spores can induce allergies and worsen respiratory ailments, including asthma (Wark and Warner, 1981, UNICEF, 2019).

Taking into account these factors, the responsiveness of air quality to classroom adjustments highlights the importance of adequate ventilation, routine maintenance of the heating, ventilation and air conditioning (HVAC) system (when applicable), efficient cleaning protocols, and fostering awareness of IEQ among students and staff.

NZ is one of seven countries meeting WHO air quality standards (IQAir, 2023). According to the World Air Quality Report (2023), NZ has emerged as one of the world's cleanest countries in terms of air quality. The baseline for the report, which measures fine particulate pollution, known as PM_{2.5} (particulate matter), is 5 µg/m³ (micrograms per cubic meter). NZ achieved an impressive air quality score of 4.3 µg/m³, indicating exceptionally clean air (Bywater, 2021).

However, this was not always the case. The first study on NZ health and air pollution in 2007 (HAPINZ 1.0) undertaken by Fisher et al. (2007), which was later updated by Kuschel et al. (2012), estimated that air pollution from all sources in NZ was responsible each year for approximately 2,300 premature deaths, nearly 1,200 hospitalisations and more than 2.9 million restricted activity days at a total cost of NZ\$8.4 billion at June 2010 (Environmental Health Indicators New Zealand, 2023). In recognition of this, the Ministry for the Environment and Waka Kotahi (in partnership with Te Manatū Waka Ministry of Transport and Ministry of Health) commissioned a new update – HAPINZ 3.0 – in 2019 to better reflect the air pollution health impacts experienced by New Zealanders and to update the effects for 2016 (Ministry for the Environment and Waka Kotahi NZ Transport Agency, 2022).

Recognising that air and air quality are both *taonga* and a part of *kaitiakitanga* for Māori, the HAPINZ 3.0 study is also named *He rangi hauora he iwi ora*, which translates to "healthy air means healthy people". (Ministry for the Environment and Waka Kotahi NZ Transport Agency, 2022).

- A *taonga* in Māori culture refers to a treasured item, whether tangible or intangible.
- A *kaitiaki* is a guardian, and the process and practices of protecting and preserving the environment are known as *kaitiakitanga*.

The exceptional air quality in NZ has significant positive implications for **natural ventilation in classrooms, as required by MoE**, for the following reasons:

1. **Improved IAQ:** Naturally ventilating classrooms become highly beneficial with such clean outdoor air. Opening windows and doors allows fresh, low-pollutant air to circulate, reducing indoor air pollutants, and creating a healthier learning environment.
2. **Reduced reliance on mechanical ventilation:** Clean outdoor air means that schools can rely more on natural ventilation methods, potentially reducing the need for energy-intensive mechanical ventilation systems. This can lead to energy savings and lower operational costs for schools (Apte et al., 2002; Cutler-Welsh, 2006).
3. **Enhanced cognitive function:** Studies have shown that better air quality is associated with improved cognitive function. Students in naturally ventilated (NV) classrooms with clean air may experience better concentration, memory, and overall academic performance (X. Zhang et al., 2017).
4. **Health benefits:** Exposure to clean air can reduce the risk of respiratory problems, allergies, and other health problems associated with poor air quality. This could lead to fewer sick days and better general health for students and teachers (Toyinbo, 2023).
5. **Comfort and well-being:** Natural ventilation with clean air can create a more comfortable and pleasant learning environment, which can improve student and teacher satisfaction and well-being (Sutherland et al., 2022).
6. **Cost-effective solution:** Using natural ventilation in a country with such clean air is a cost-effective way to maintain good IAQ without significant investments in air purification systems (Diaz et al., 2021; Korsavi et al., 2020).
7. **Environmental education opportunities:** The ability to use natural ventilation effectively can serve as a practical example in environmental education,

teaching students about air quality and sustainable building practices (Almeida et al., 2017; Gaihre et al., 2014).

8. **Reduced CO₂ levels:** Natural ventilation helps maintain lower CO₂ levels in classrooms, which is crucial to maintain alertness and cognitive function among students and teachers (X. Zhang et al., 2017).
9. **Flexibility in classroom design:** Architects and school planners can design classrooms that maximise natural ventilation, which can lead to more open and flexible learning spaces (Ministry of Education, 2023).
10. **Pandemic considerations:** In the context of airborne diseases such as COVID-19, the ability to effectively ventilate classrooms with clean outdoor air can be a factor in reducing transmission risks (Ali and Waters, 2021; Romero et al., 2023).

It is important to note that while natural ventilation is highly beneficial in clean air conditions in NZ, it remains essential to balance it with other factors such as temperature control, noise reduction, and security considerations. In addition, monitoring IAQ and adjusting ventilation strategies is crucial to ensure optimal learning conditions.

2.4.1 Carbon dioxide and metabolic carbon dioxide (CO₂)

Metabolically generated, or bio-effluent, CO₂ refers to the CO₂ emissions produced by living organisms and their activities within indoor environments. It originates primarily from students' respiration, but can also be released by pets, plants, and other microorganisms (Winck et al., 2022). In enclosed spaces, such as classrooms, metabolically generated CO₂ accumulates over time if ventilation is inadequate, leading to elevated levels of CO₂ in indoor air (Mansouri et al., 2022). **Moving forward, for conciseness, it will be assumed that references to 'CO₂' pertain to metabolically produced CO₂ unless otherwise specified.**

This CO₂, a colourless and odourless gas, is commonly used as an indicator of IEQ. This is because the concentration of CO₂ in the air is a valuable benchmark to evaluate the performance of ventilation systems in buildings (Chatzidiakou et al., 2015; Satish et al., 2012).

Elevated CO₂ levels indicate insufficient ventilation, inadequate air exchange, or overcrowding within a space. High concentrations of CO₂ can cause discomfort, drowsiness, and difficulty concentrating and may indicate the potential presence of other indoor air pollutants (Mansouri et al., 2022).

Proper ventilation is the key to mitigating and controlling CO₂ in IEQ. Well-designed ventilation systems ensure adequate fresh air exchange and the removal of contaminants, including CO₂, from the indoor environment (Kierat et al., 2022). Sufficient airflow and the introduction of outdoor air help dilute and reduce CO₂ levels (Thoua et al., 2022).

The story behind the ASHRAE '1000 ppm' baseline

In the late 19th century, Max von Pettenkofer, a prominent German chemist and hygienist, challenged the prevailing notion that CO₂ was the primary culprit behind the adverse effects associated with poor ventilation. Instead, he proposed that organic materials emanating from human skin and lungs were responsible for these adverse effects. Pettenkofer suggested that CO₂ should not be considered a direct cause of discomfort but rather an indicator of deterioration of air quality, or "vitiating air" (Persily, 2015, 2022; X. Zhang et al., 2017).

As the 20th century dawned, a series of studies by researchers such as John Shaw Billings, Charles-Édouard Guillaume, Carl Flügge, and Leonard Hill further expanded our understanding of IAQ. Their work demonstrated that the combination of elevated temperatures and odours in crowded and poorly ventilated spaces was a significant source of discomfort for occupants. This research shifted the focus from CO₂ alone to a more comprehensive view of IAQ factors (Persily, 2015; X. Zhang et al., 2017).

In the 1930s, Constantin Yaglou and his predecessor Louis Lemberg conducted groundbreaking research on the human perception of body odour. Their work showed that the intensity of perceived body odour could serve as a criterion to determine the appropriate ventilation rates. This approach led to the development of ventilation guidelines that recommend airflow rates of approximately 7.5 to 10 L/s.p. (15 to 20 cubic feet per minute) per person. Again, CO₂ was not considered a pollutant in itself but rather an indicator of body odour concentration (Persily, 2015,

2022; X. Zhang et al., 2017).

The latter half of the 20th century saw further refinement of these concepts through the work of researchers like P. Ole Fanger, William S. Cain and Yoshio Iwashita. Their studies corroborated and expanded on the findings of Yaglou and Lemberg, providing a more nuanced understanding of human perception of IAQ and comfort (X. Zhang et al., 2017).

This body of research on odour perception and its relationship to ventilation requirements played a crucial role in the shaping of ventilation standards developed by organisations such as ASHRAE and the European Committee for Standardisation (CEN). These standards provide guidelines for maintaining an acceptable IAQ in various types of buildings (Persily, 2015, 2022).

The 1989 edition of ASHRAE's ventilation standard, known as Standard 62 (later renamed Standard 62.1), included a CO₂ limit of 1000 ppm (Persily, 2015). However, this limit was removed from subsequent editions due to widespread misinterpretation. Many practitioners incorrectly assumed that maintaining CO₂ levels below 1000 ppm would ensure good IAQ, overlooking other important factors such as temperature, humidity, and other pollutants (ASHRAE, 2022b).

The evolution of our understanding of IAQ and ventilation requirements highlights the complexity of the subject and the need for a multifaceted approach to maintain healthy indoor environments. Although CO₂ remains an important indicator of air quality, modern ventilation standards and practices consider a wider range of factors to ensure the comfort and well-being of the occupants.

2.4.2 Thermal comfort environment

This section laid the foundations for an empirical examination of TC models and their connections with the indoor environment, specifically focussing on children's thermal perception in classrooms with natural ventilation. Initially, the section presents an overview of the TC models and their applicability within educational settings. Subsequently, the research examines the various determinants affecting TC in such environments. The final part of the section establishes the criteria for IEQ

tailored to the needs of young learners in primary schools.

TC refers to the body's requirement to maintain a consistent core temperature of around 37 °C, which is vital for overall health and optimal performance of bodily organs, especially the brain, as articulated by Nicol et al. (2012). Achieving this stability hinges on a sophisticated process known as "thermoregulation," the intricate interplay between the body and its surrounding environment.

The ASHRAE 55 standard defines TC as a multifaceted cognitive assessment influenced by physiological, physical, and psychological factors (ASHRAE, 2020). Comfort hinges on maintaining specific parameters such as precise skin and core body temperature ranges, limited skin moisture, and reduced physiological exertion for temperature regulation. Behavioural responses also impact TC, including actions such as changing clothing, changing activity levels, moving to a different location, adjusting room temperature, opening windows, expressing discomfort or leaving the uncomfortable area (ASHRAE, 2020; Fanger, 1970).

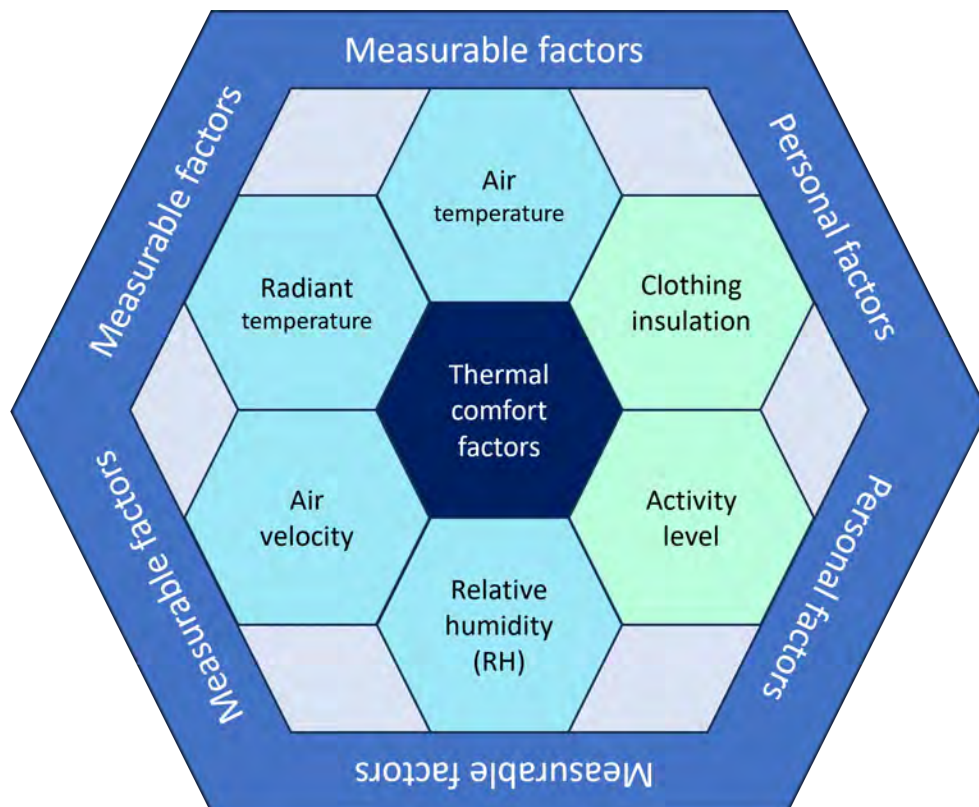
Understanding the dynamics of thermal comfort requires a variety of methodologies, including analysis of the heat balance and investigations of physiological and psychological factors (Nicol et al., 2012). Physicists study heat transfer to and from the body, thermal physiologists examine heat generation and utilisation, and thermal psychologists explore subjective perceptions of environmental conditions. Building engineers and designers synthesise these interconnected elements to create structures that meet the thermal comfort needs of the occupants (X. Jia et al., 2024; Zivin and Shrader, 2016).

Olgyay pioneered TC in architectural design with his bioclimatic approach (Zuhairy and Sayigh, 1993). The design of TC aims to establish indoor environments that meet the comfort needs of the occupants, ensure a comfortable temperature, protect health, manage energy use, and inform standards, guidelines and regulations for indoor temperatures (Auliciems, Szokolay, et al., 1997; Nicol et al., 2012).

The thermal environment affects indoor heat transfer and significantly influences the perception of temperature and TC by individuals (ASHRAE, 2020). TC, a subjective evaluation of the thermal environment, is primarily shaped by four key environmental parameters, as shown in Figure 2.4 (Macpherson, 1973). Personal

factors such as clothing insulation and activity level intertwine these physical variables (ASHRAE, 2020). Moreover, gender (Karjalainen, 2012), age (Griefahn and Künemund, 2001), culture (Knez and Thorsson, 2006), exposure time (Nicol and Humphreys, 2002), and physiological adaptation (M. Luo et al., 2016) further complicate the TC landscape.

FIGURE 2.4: Factors Impacting Thermal Comfort



Source: adapted from Brandemuehl, 2005

TC is subjective, varying due to individual psychological and biological distinctions, alongside cultural and social influences (Fanger, 1970). Fanger emphasises the importance of providing acceptable thermal conditions to maximise the comfort of the occupants (Fanger, 1970). ASHRAE 55 states that TC is achieved when more than 80% of the occupants find the indoor environment thermally acceptable, highlighting the importance of meeting the subjective perceptions of the occupants (ASHRAE, 2020). Building engineers must consider individual temperature preferences and physiological and psychological factors when designing TC to ensure occupant satisfaction.

The thermal environment comprises air temperature, radiant temperature, air humidity and airflow velocity, which collectively influence TC along with metabolic heat production and clothing insulation (Macpherson, 1973; Huh and Brandemuehl, 2008). **Figure 2.4** illustrates these key parameters. For clarity, this discussion will address each factor individually, excluding the mean radiant temperature, which is not relevant to this study.

Air temperature (t_a)

Air temperature, as defined by ASHRAE 55 (ASHRAE, 2020), refers to the temperature surrounding the student. It is typically measured using a dry bulb thermometer and is expressed in degrees Celsius (°C). The air temperature is a critical factor in determining the loss of convective heat from the body and is of significant importance in achieving TC (Auliciems, Szokolay, et al., 1997).

Air velocity (v_a)

Air velocity impacts temperature, RH, and air renewal rates, influencing air quality and contaminant presence (Raju et al., 2020). Anemometers measure air velocity in metres per second, and humans typically perceive air movement at 0.2 m/s, where higher velocities can increase convective heat transfer, producing a cooling effect (Fanger, 2006). The personal perception of air velocity can affect TC; excessive cooling can compromise immunity, leading to colds and hypothermia (Auliciems, Szokolay, et al., 1997). Air renewal levels directly affect health outcomes, requiring balance to avoid excess or insufficient air changes (Franklin, 2007; Raju et al., 2020).

Studies recommend indoor airspeeds ranging from 0.2 to 1.50 m/s, with 0.2 m/s as the upper limit in air-conditioned spaces without occupant control (ASHRAE, 2020). Occupant satisfaction in the indoor climate should be prioritised over solely focusing on air movement (Toftum et al., 1998). Preferences for air movement vary, with cold-sensitive individuals preferring less movement and warm-sensitive individuals preferring more, especially around 22-23 °C (de Dear and Brager, 2002; Toftum et al., 1998).

Draught discomfort predictions often do not align with occupants' real-world preferences, as occupants in neutral-to-warm conditions may accept and even prefer higher airspeeds than predicted (H. Zhang et al., 2007). Higher air velocities

can provide a cooling effect due to increased evaporation of moisture on the skin, enhancing TC, particularly at higher temperatures (Wigö and Knez, 2005; Toftum et al., 1998).

Individual preferences for air movement and temperature can differ, influenced by factors such as HR, clothing, and metabolic rates (Brager and de Dear, 1998; de Dear et al., 1998).

Therefore, the relationship between air temperature and air velocity is multifaceted and depends on various individual and environmental factors.

Relative humidity

RH denotes the current level of water vapour in the air relative to its maximum capacity at that temperature. At 100% RH, dew point is reached, causing condensation and precipitation. RH levels exceeding 90% intensify temperature perceptions, while RH below 20% can irritate the eyes, nose, and throat (Davis et al., 2016; Wolkoff, 2018). Indoor RH is crucial; above 65%, mould and microorganisms thrive, releasing allergens and toxins, triggering respiratory problems (Ghosh et al., 2022). High RH improves VOC emissions and deteriorates IAQ, while low RH exacerbates respiratory problems and allergens (Hess-Kosa, 2018; Wolkoff, 2018). Maintaining RH between 40-60% at 18-24 °C is recommended for optimal TC&V (ASHRAE, 2020).

In comfort zones, RH minimally affects thermal sensation, facilitating body cooling through evaporation, though high RH can impede natural cooling mechanisms (Huh and Brandemuehl, 2008). The relative humidity of the equilibrium (ERH) corresponds to the activity of water of a material (a_w) and influences microbial growth; xerophilic fungi thrive in ERHs of 70%, with similar impacts on the survival of airborne bacteria below and above 60% RH (Boulic, 2012).

Management of the humidity ratio, particularly in the context of HVAC systems, involves maintaining the balance of moisture in the air to ensure comfortable and safe environments. When applying humidity ratio management to school settings, providing a comfortable and healthy learning environment for students and staff is

important while considering schools' specific activities and structures. This is how the four components could be tailored for a school setting:

1. **Control at the source:** Minimise moisture generation by managing activities that produce humidity, such as cooking in the cafeteria, showering in locker rooms, and art or science projects that involve water. Use localised exhaust fans to vent moisture-laden air directly outside of these areas.
2. **Ventilation:** Implement a ventilation system to bring in fresh outdoor air and exhaust stale indoor air while balancing humidity levels. For classrooms with many students, proper ventilation is crucial because human respiration and perspiration can contribute significantly to indoor humidity (Davis et al., 2016; Tanabe and Kimura, 1994).
3. **Insulation:** Ensure that the school building is well insulated to maintain a consistent indoor temperature, thus preventing condensation on surfaces, which can occur when there is a temperature difference between indoor air and walls or windows. An insulated building envelope also helps to reduce heating and cooling costs (Fullbrook et al., 2022).
4. **Dehumidification and heating:** Increasing the temperature will reduce the RH in the same humidity ratio. In humid climates or during certain seasons, use dehumidifiers to maintain comfortable TC and humidity levels in classrooms, gymnasiums, and other school facilities. Portable or fixed dehumidification units can be beneficial in areas that are prone to dampness or lack adequate natural ventilation (Davis et al., 2016; McIntyre, 1978).

Schools regularly monitor indoor humidity levels using hygrometers and maintain HVAC systems (if available) to ensure that they adequately address school air quality needs. By following these management strategies, schools can provide a conducive learning environment that promotes students' well-being and academic performance. Collectively, these strategies provide a comprehensive approach to regulating the humidity ratio within buildings, ensuring comfort, preserving structural integrity, and maintaining healthy IAQ (Bonell et al., 2014; Wolkoff, 2018).

Although specific research encompassing children as participants with RH as an independent variable is currently lacking, further examination of the pertinent literature has revealed that adults exposed to increased RH levels experienced a

reduction in memory capacity and psychomotor speed (Adan, 2012; Taylor et al., 2016).

Managing RH is crucial for indoor comfort, but clothing insulation also plays a vital role in thermal comfort and energy efficiency. **However, this study does not include clothing insulation assessment** as the students did not wear school uniforms, making it impractical to determine individual "clo" units during cognitive testing.

Activity level

Metabolism involves the derivation of energy from food through oxidation, influencing the metabolic rate expressed in watts per square metre (W/m^2) or metabolic equivalent of units of tasks (MET), with physical exertion increasing this rate and affecting TC (Glazier, 2014). Interactions between factors such as air temperature, air velocity and skin temperature produce varied effects on the body, with cooling effects occurring when the air temperature is lower than the skin temperature and the air velocity increases, while heating effects result from air temperatures exceeding the skin temperature (Korsavi et al., 2020; Macpherson, 1973). Achieving optimal balance requires considering personal preferences, activity levels, and clothing choices to prevent excessive warmth or coldness and maintain appropriate air moisture levels for comfort. Individual preferences and environmental needs may vary, underscoring the importance of consulting guidelines from organisations such as ASHRAE for customised recommendations in diverse contexts.

Understanding these parameters is crucial for designing environments that improve occupant TC. By accounting for metabolic rates, activity levels, and clothing insulation, designers can create spaces that promote ideal thermal conditions for students, facilitating comfort and establishing relevant clothing guidelines across different settings.

Thermal comfort models

When discussing TC in indoor environments, several models and approaches are used to understand and predict how satisfied people will be with their thermal environment. These models are crucial for the design of HVAC systems and for

establishing comfortable and healthy indoor environments, including but not limited to:

- Predicted Mean Vote (PMV), (Fanger, 1970)
- Predicted Percentage Dissatisfaction (PPD) model, (Fanger, 1970)
- the Adaptive Approach, (Nicol and Humphreys, 2002)
- the Personal TC model (J. Kim et al., 2018; Liu, 2018) which employs principles of machine learning.

The thermal environment consistently and predictably influences certain aspects of cognition, especially when tolerance limits are approaching (P. A. Hancock et al., 2007).

1. Predicted Mean Vote (PMV)

- PMV is a quantitative model developed by P.O. Fanger in the 1970s to predict the mean value of the votes of a large group of people on a 7-point thermal sensation scale (from -3.0 cold to +3.0 hot) (Fanger, 1970).
- It is based on a heat balance equation that includes variables such as air temperature, mean radiant temperature, air speed, humidity, clothing insulation, and metabolic rate (Fanger, 2006).
- The PMV is an index that predicts the average thermal sensation of a group but does not account for individual variations of the TC (Enescu, 2017).

2. Predicted Percentage Dissatisfied (PPD) Model

- The PPD model is closely related to PMV. It is an empirical model to predict the percentage of people who are likely to feel thermally dissatisfied with a particular environment (Fanger, 1970).
- It is based on the assumption that there is a statistical distribution of TC preferences around the PMV score, while PMV moves away from zero (neutral thermal sensation), and the PPD increases (Fanger, 1970).
- It does not consider individual differences or adaptability and prescribes a standard condition that should satisfy the largest number of occupants (Enescu, 2017).

3. Adaptive Approach

- The Adaptive Approach recognises that humans can adapt their behaviour, clothing, and environment based on their thermal experience and, as such, can tolerate a wider range of temperatures (Nicol et al., 2012).
- This approach is based on observed behaviours and preferences in different climates and considers that people's TC depends on their accustomed temperatures (Nicol et al., 2012).
- It allows flexibility and is often considered more sustainable as it can reduce energy use in buildings since occupants adapt to a wider range of temperatures (Enescu, 2017).

4. Personal Thermal Comfort Model

- Personal TC models focus on individual satisfaction rather than group averages. These models take into account personal differences, including metabolic rates and clothing insulation, but also other factors such as sex, age, physical condition, psychological factors, and individual thermal history (J. Kim et al., 2018; Liu, 2018).
- They recognise the subjective nature of TC and often use personal sensors or smartphone applications to collect individual data for the evaluation of TC in real time (J. Kim et al., 2018; Liu, 2018).
- These models aim to tailor the thermal environment to individual needs and can be part of personalised climate control systems in advanced HVAC designs (J. Kim et al., 2018; Liu, 2018).

One of the most notable criticisms revolves around a universal "neutral" temperature. The application of PMV in NV buildings has been questioned by de Dear and Brager (1998), who argue that the rigid cool air paradigm for TC, which requires significant energy consumption for mechanical cooling, may be overly restrictive. They suggested that it may not be an appropriate criterion when deciding whether or not to install HVAC systems (de Dear et al., 1998). In response to such criticisms, the widely accepted 'adaptive comfort model' emerged, shifting the paradigm and recognising the importance of considering individual adaptation and preferences when defining TC. This model acknowledges the dynamic nature of comfort and the need to account for various climatic and environmental conditions (van Hoof et al., 2010).

Comparison of models

- **Scope:** Although PMV and PPD aim to predict the satisfaction of a larger population, the Adaptive Approach and Personal TC models acknowledge individual differences. The first two are prescriptive and general, while the latter are descriptive and personalised (Enescu, 2017; Teli et al., 2012).
- **Flexibility and adaptation:** The Adaptive Approach and Personal TC models consider the dynamic nature of human thermal adaptation. At the same time, PMV and PPD are more static, based on steady-state conditions (Nicol et al., 2012).
- **Predictive vs reactive:** PMV and PPD predict comfort based on a fixed set of parameters, while the Adaptive Approach and Personal TC models can adapt to personal preferences and behavioural changes over time (Enescu, 2017; Nicol et al., 2012).
- **Individual vs group:** PMV and PPD models seek to satisfy as many people as possible without personalisation, while the adaptive approach allows individual behavioural adjustments, and the personal TC model targets individual comfort optimisation (Enescu, 2017; Nicol et al., 2012).
- **Energy efficiency:** The Adaptive Approach and Personal TC models can potentially lead to more energy-efficient building operations by allowing and harnessing natural thermal variations and personalised comfort systems. PMV and PPD often lead to narrow temperature control and potentially higher energy use (Liu, 2018; Nicol and Humphreys, 2002).
- **Technological demands:** Personal TC models may require more sophisticated technology to monitor and respond to individual comfort needs. PMV and PPD are based on calculations from standardised variables (Fanger, 2006).

Each approach has its place: PMV and PPD are helpful in environments where individual control is not feasible and where a compromise is necessary for the comfort of the majority (e.g., large offices and shopping malls). The Adaptive Approach is particularly suitable for NV buildings and areas with significant outdoor-indoor interaction. The Personal TC model is emerging with smart building technologies, especially in spaces where individual comfort can be independently

controlled, such as personal office spaces or residential units.

The PMV model has limitations when it comes to accurately predicting the TC of children. Children have unique physiological and behavioural characteristics that can affect their TC requirements differently from adults. Factors such as higher metabolic rates, different body surface area-to-mass ratios, and the tendency to be more active can affect how children perceive and experience thermal conditions (Enescu, 2017; Schweiker et al., 2018).

Choosing the best TC model for a school classroom environment depends on several factors, including climate, the flexibility of the building's HVAC system, and the ages and activities of the students.

In a school classroom setting, the following considerations might inform the choice:

1. Adaptive Approach

- In places with moderate climates where it is feasible to use natural ventilation for significant parts of the year, an adaptive model might be particularly suitable because it allows for natural fluctuations in temperature and recognizes the ability of students and teachers to adapt to these changes (Kumar and Singh, 2021; Miranda et al., 2022).
- The adaptive model aligns with educational environments because it acknowledges that the occupants can make personal adjustments, such as changing clothing or the use of personal fans or heaters (Nicol et al., 2012).

2. PMV-PPD Models

- These models may be more appropriate in environments that require tight temperature control due to extreme outdoor conditions, where natural ventilation is insufficient to maintain comfortable indoor conditions (ISO7730, 2005).
- For classrooms with centralised HVAC systems, these models can inform the initial design and settings of heating and cooling systems to meet the comfort needs of most of the occupants (J. Kim et al., 2018; Schweiker et al., 2018).

- However, it may be challenging to meet everyone's comfort levels, since these models do not account for individual variations well, and people, especially children, may have diverse TC needs (Liu, 2018).

The adaptive approach is generally aligned with sustainability goals and tends to be more energy efficient, a significant consideration for schools (Brychkov et al., 2023). It is also practical in terms of maintenance and operational costs. However, the choice is strongly influenced by the specific conditions of the school, including the design of the classroom, the local climate, and the preferences of the occupants (Baker, 2012; Zuhairy and Sayigh, 1993).

Recent trends emphasise creating more responsive and individualised learning environments, noting that comfort can enhance students' focus and learning. This suggests potentially advancing towards nuanced models like the Personal TC Model, provided the technology is feasible. However, large-scale implementation requires substantial investment in advanced climate control systems (J. Kim et al., 2018).

A hybrid approach that integrates elements from the PMV-PPD and Adaptive models, alongside considerations of human behaviour, is likely most effective for classroom settings. This approach can include adjustments such as varied clothing, personal fans or heaters, and allowing personal control where feasible, thus catering to diverse TC needs within a relatively stable overall temperature as predicted by PMV-PPD models.

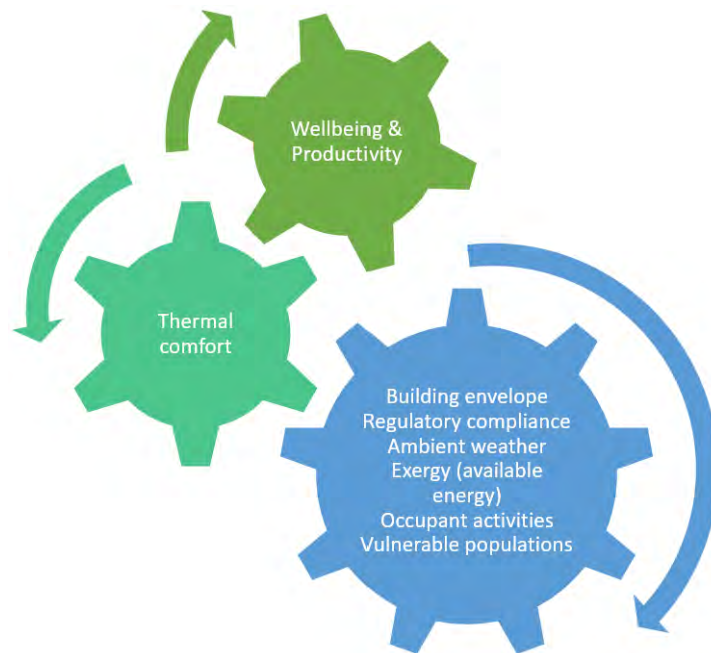
Integrating all three considerations—Adaptive, PMV-PPD, and human behaviour—into building HVAC and ventilation system designs can create thermally comfortable and health-promoting environments. An adaptive approach emphasises letting the behaviour of the occupant guide the operation of the HVAC system, making it more responsive and energy efficient. It avoids overheating, overcooling, or overventilating, ultimately optimising energy use and improving indoor environmental quality.

Purpose of using TC models in a classroom

In classroom settings, TC models are crucial for assessing and optimising the comfort of students and teachers with respect to temperature and air quality. These models help maintain an environment where temperature, humidity, airflow, and heat from

external sources remain pleasant, thus fostering a focused and effective learning atmosphere. Using TC models ensures that the thermal conditions align with the comfort of the student and staff, promoting a conducive learning environment. **Figure 2.5** illustrates why TC models are integral to IEQ studies.

FIGURE 2.5: *Summary of Thermal Comfort Models Impact*



Source: Authors Own

Classroom temperature has a direct impact on student comfort and engagement, with temperature extremes that can alter concentration and affect health (Ganesh et al., 2021; Jiang et al., 2018; Kaushik et al., 2020; Rony and Alamgir, 2023). Optimal temperatures improve attention and improve learning outcomes. Given the varying sensitivity to temperature fluctuations among children and individuals with health issues, customised TC models are necessary to ensure well-being (Mamani et al., 2022). These models provide a standardized method for adjusting room temperature, considering airflow and humidity, which creates a comfortable and high-quality educational environment aligned with standards like Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Methodology (BREEAM), or WELL Building Standard (WELL) (Berger et al., 2023).

Proactively adjusting temperatures based on TC models prevents discomfort, reduces the need for personal heating or cooling devices, and conserves energy (Enescu, 2017; L. Jia et al., 2021). Using TC data is essential to design efficient HVAC systems that guarantee student comfort and focus, minimising temperature-related distractions (L. Jia et al., 2021).

2.4.3 Defining TC&V criteria for primary school children

The predominant posture of primary school students during instructional sessions, including lessons, class activities, storytime or play-based learning, is typically sedentary, seated at their desks with limited physical activity beyond writing or typing notes (Burn et al., 2022; Honeybourne, 2018). **In light of this, the effect of physical activity on thermal sensation in the study is considered minor.** This specific aspect is consistent with the nature of the activities central to this research.

Most secondary schools and some primary and intermediate schools in NZ have rules requiring students to wear a school uniform (Community Law, 2023). Specific regulations on school uniforms can vary significantly from one institution to another. It is worth noting that in the context of this case study, the students in Years 5 and 6 do not adhere to a uniform dress code. **This presents a limitation in the context of the study, as it excludes the possibility of taking standardised measurements of the insulation values of clothing (clo) for student participants.** Furthermore, it is not practicable within the boundaries of this investigation to measure individual metabolic rates, which are crucial factors in assessing TC.

2.4.4 Summary of factors influencing air quality and thermal comfort

In summary, this section provides an overview of the impact of air quality and thermal comfort on educational environments, focussing on classrooms. It discusses the composition of indoor air, pollutants and factors affecting air quality, such as CO₂ levels and ventilation. In addition, it explores thermal comfort models, including the PMV, PPD, Adaptive Approach, and Personal Thermal Comfort Model. The importance of these models in maintaining a comfortable learning environment is emphasised by considering factors such as temperature, humidity, and airflow. The section highlights the importance of implementing

customised TC criteria for primary school children to enhance their comfort, focus, and general well-being in the classroom.

2.5 Regulations and guidelines

The selection of regulatory bodies for this study is deliberate and focused, focussing on the World Health Organisation (World Health Organization et al., 1987), ANSI/ASHRAE Standard 55 (ASHRAE, 2020) and Standard 62.1 (ASHRAE, 2022a), and Clause G4 of the NZBC 'Ventilation' (Building Industry Authority of New Zealand, 1998) and the NZ Standard for Ventilation and Air Quality (Standards New Zealand, 1990a), and the NZ MoE Designing Quality Learning Spaces (DQLS) Guidelines (Fullbrook et al., 2022). These specific bodies have been chosen for several key reasons:

1. **Global and local relevance:** The WHO provides internationally recognised standards, while ASHRAE offers internationally accepted guidelines for building systems. Including NZ-specific standards (G4, NZS 4303, and MoE Guidelines) ensures that the study is grounded in a local regulatory context.
2. **Comprehensiveness:** Together, these bodies cover a wide range of IEQ factors, including temperature, relative humidity, ventilation, and air quality, providing a holistic framework for assessment.
3. **Educational focus:** The NZ MoE's guidelines are specifically tailored to learning environments, aligning closely with the study's focus on school settings.
4. **Established credibility:** These organisations are recognised leaders in their respective fields, offering well-established and widely accepted standards.
5. **Applicability to the NZ context:** Although the ASHRAE standards are international, it is important to note that NZS4303 and G4 are based on the ASHRAE standards but are adapted for NZ conditions. This adaptation ensures that the study considers standards that are directly applicable to the local environment.
6. **Manageable scope:** Given the multitude of guidelines available worldwide, focussing on these specific bodies allows for a more in-depth and manageable analysis within the constraints of this study.

7. **Relevance to research questions:** These selected standards directly address the study's focus on IEQ in educational settings and the appropriateness of adult-centric standards for children.

By focussing on these particular regulatory bodies, the study can provide a focused, relevant and context-specific analysis of IEQ standards as they apply to NZ schools. This approach examines international best practices and local requirements, allowing an assessment of IEQ in educational environments.

2.5.1 The World Health Organisation Air Quality Guidelines

The World Health Organisation Air Quality Guidelines (AQGs) (World Health Organization et al., 1987) highlight the critical importance of IAQ and CT in educational settings. Recognising that children spend a substantial portion of their time in classrooms, these guidelines emphasise the need for standards that safeguard students' health and well-being. The WHO developed minimum guidelines for the levels of temperature, ventilation and pollutants to mitigate the health risks associated with suboptimal indoor environmental conditions. The WHO has not published recommended limits for indoor RH or guidelines on CO₂.

2.5.2 ASHRAE Standard 55

ASHRAE Standard 55 (ASHRAE, 2020) sets out thermal comfort guidelines for indoor spaces, considering factors such as air temperature, radiant temperature, RH, air velocity, metabolic rate, and clothing insulation. It establishes an acceptability limit of $T_{\text{comf}} \pm 3.5^{\circ}\text{C}$ for 80% of occupants. Initially designed for sedentary office settings, the standard extends to classrooms, where activities are typically aligned with very light exertion levels (1.3 MET). ASHRAE recommends levels of RH between 40-60% to prevent mould growth and ensure comfort. The standard's 'adaptive model' accounts for outdoor temperatures affecting indoor comfort in NV buildings, supported by research on occupant adaptation. However, adapting these metrics for children's distinct thermal needs and activity levels in educational settings remains challenging, as the standard primarily focusses on adult office environments.

2.5.3 ASHRAE Standard 62.1

ASHRAE Standard 62.1, revised in 2019 and 2022 (ASHRAE, 2022a), sets ventilation requirements to ensure healthy indoor environments in various buildings, including educational facilities. The standard focusses on adequate ventilation rates to manage air pollutants and create comfortable spaces, which is critical to supporting student and staff health and school performance (ASHRAE, 2022a). It specifies minimum outdoor air ventilation rates based on occupancy and function, ensuring suitable air quality for various activities within school premises (ASHRAE, 2022a). Furthermore, the standard provides guidance on operational practices to maintain long-term IAQ and system effectiveness in educational settings, balancing occupant health with energy efficiency (ASHRAE, 2022a). ASHRAE Standard 62.1-2022 recommends a standard classroom ventilation rate of 8 L/s.p, serving as a benchmark for designing ventilation systems to meet acceptable school ventilation levels (ASHRAE, 2022a).

2.5.4 NZ Building Code Clause G4; the New Zealand Standard for Ventilation and Air Quality (NZS 4303, 1990) and MoE (DQLS series) Guidelines

NZBC clause G4 (Building Industry Authority of New Zealand, 1998) and NZS4303:1990 (Standards New Zealand, 1990a) work together to ensure proper ventilation in buildings. This is how they relate:

1. NZBC Clause G4:

- This is a performance-based code that sets the objectives for ventilation in buildings.
- It requires buildings to have outdoor air ventilation that maintains air purity and prevents the accumulation of odours and contaminants.
- It applies to all buildings and specifies different requirements for occupied spaces, accommodation units, and other spaces.

2. NZS4303:1990 (Ventilation for Acceptable Indoor Air Quality):

- This standard provides one means of complying with Clause G4.
- Provides specific guidance on ventilation rates, air distribution, and other factors to achieve an acceptable IAQ.

- The standard specifies minimum ventilation rates for various spaces and occupancies.
- This Standard is based on the original ASHRAE 62:1989 Standard.

There are several key points to understand about the relationship between these two standards:

1. **Basis for development:** NZS4303:1990 was developed using ASHRAE 62:1989 as a foundational reference. The ASHRAE standard is a well-established benchmark in ventilation and IAQ, providing a comprehensive set of guidelines to maintain an acceptable IAQ.
2. **Adaptation to local conditions:** Although NZS4303:1990 is based on ASHRAE 62:1989, it has been adapted to meet the unique environmental, cultural, and regulatory conditions of NZ. This localisation ensures that the standards are relevant to the specific climate, building practices, and indoor environments in NZ.
3. **Differences in requirements:** There are differences in specific ventilation rates, acceptable levels of contaminants, and other technical parameters. These differences are in response to the varied requirements of local environments.
4. **Regulatory context:** NZS4303:1990 is mandated within NZ's building regulations, whereas ASHRAE 62:1989 is a widely recognised standard in the wider international context, particularly in the United States.

A key issue of concern is that NZS4303:1990 is formulated from the ASHRAE Standard 62.1:1989 version, primarily based on odour control rather than a more comprehensive approach to fresh air supply. At that time, the main method for determining ventilation rates was based on controlling the odours to a level acceptable to a substantial majority (usually 80%) of visitors entering a space. The underlying assumption was that if enough ventilation was provided to control body odours to an acceptable level, it would suffice to dilute other indoor air contaminants. This approach did not directly address other IAQ concerns or specific pollutants, which was later recognised as a limitation.

ASHRAE Standard 62.1:2022 has evolved significantly from its earlier versions, moving from the primarily odour-based approach to a more comprehensive method to ensure adequate IAQ. Below are a few of the major highlights (ASHRAE, 2022a):

1. Ventilation Rate Procedure (VRP):

- This is the primary method in the current standard. It specifies minimum ventilation rates based on both occupancy and floor area. These rates are determined by considering various contaminants and their sources, not just odours.

2. Indoor Air Quality Procedure (IAQP):

- This is an alternative performance-based method. It allows for calculating outdoor air requirements to maintain specific contaminant concentrations below certain thresholds.

3. Outdoor air quality:

- The standard considers outdoor air quality, recognising that, in some cases, outdoor air may need treatment before being introduced indoors.

4. Occupancy categories:

- Defines different occupancy categories with specific ventilation requirements based on expected activities and contaminant generation.

5. Intermittent occupancy:

- Addresses spaces with intermittent or variable occupancy, allowing for ventilation optimisation.

This evolution reflects a more nuanced understanding of IAQ, recognising that the fresh air supply must be tailored to specific uses of space, occupancy patterns, and potential contaminant sources. The standard now aims to provide a healthier indoor environment while considering energy efficiency and practicality in building operations.

In summary, while NZS4303:1990 and ASHRAE 62:1989 share a common goal of ensuring acceptable IAQ through adequate ventilation, they are not equivalent. The NZ standard is tailored to fit its local environment's needs and conditions, making it relevant and influential within NZ building practices (however outdated).

However, NZS4303:1990, the NZ Standard for Ventilation for Acceptable IAQ, has not been upgraded to align with more recent international standards like ASHRAE 62.1-2013 or even 62.1-2022 since COVID-19 for several potential reasons:

1. **Cost and resource constraints:** Updating standards requires significant resources, including time, expertise, and financial investment. The process involves rigorous research, stakeholder consultation, and sometimes international collaboration, which available resources might constrain.
2. **Review cycles:** Standards are typically reviewed in set cycles, which can take several years. If a standard is due to be reviewed or recently reviewed, any changes may be pending or undergoing a detailed evaluation.
3. **Evidence and data:** Decision-makers may need compelling evidence or data that indicates the need for an update. If current standards meet the necessary safety and health outcomes, there may be less impetus for change.
4. **Government policy and priorities:** The update of standards may be influenced by broader government policy and strategic priorities, which can shift resources and focus to other areas.
5. **Complementary regulatory framework:** The existence of the MoE's compliance documents, specifically the "Designing Quality Learning Spaces" (DQLS) series, which includes guidelines for IAQ and TC, may be seen as a complementary regulatory framework to NZS4303:1990. This situation could potentially reduce the perceived urgency to update the NZS4303 standard.

The DQLS guidelines are specifically designed for educational environments and can incorporate more recent research and international best practices (Fullbrook et al., 2022). They consider the unique requirements of school buildings and the needs of students and staff. As these guidelines have been updated since 2017 (Fullbrook et al., 2022) and maintained by the MoE, they can be viewed as filling gaps or addressing shortcomings in the older NZS4303 standard.

This dual system approach, where a general standard (NZS4303) is supplemented by sector-specific guidelines (DQLS), could be seen as an effective way to maintain up-to-date regulations without requiring frequent revisions of the broader standard. Decision-makers may view this as a more flexible and responsive approach, allowing faster updates to the DQLS guidelines as new information becomes available,

particularly in light of events such as the COVID-19 pandemic.

However, it is important to note that, while this approach may be pragmatic, it could lead to inconsistencies between different sectors or confusion among stakeholders who must navigate multiple guidelines and standards. It may also burden the MoE to ensure that their guidelines remain current and comprehensive.

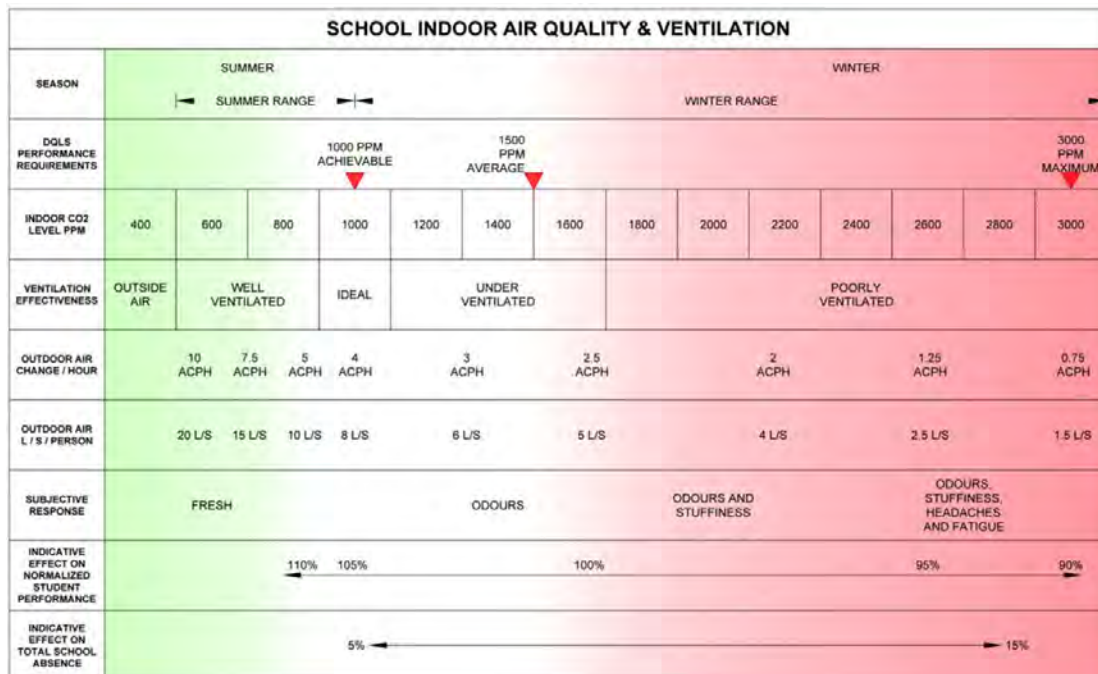
This point highlights the complexity of regulatory frameworks and the potential interaction between different standards and guidelines to address IAQ and ventilation requirements.

2.5.5 Application of regulatory documents

All IEQ-monitored data for this study will be reported against:

- Pre-COVID-19
 1. **WHO Temperature Range:** The WHO recommends maintaining a temperature range of 18 °C to 24 °C during school hours when the classrooms are occupied (World Health Organization et al., 1987)
 2. **ASHRAE Relative Humidity Range:** According to ASHRAE, the ideal RH should be between 40% and 60% if the temperature is set within the 18 °C to 24 °C range (ASHRAE, 2020).
 3. **NZBC G4 (Ventilation) and NZS 4303:1990:** This standard suggests that CO₂ levels in indoor environments should stay below 1000 ppm to ensure "acceptable odour air quality" (Standards New Zealand, 1990b; Standards New Zealand, 1990a). Additionally, the **NZ MoE's 2017 guidelines** emphasise the management of IAQ and TC in classrooms. These guidelines state that CO₂ levels should not exceed 1500 ppm, as depicted in **Figure 2.6**, with a daily average requirement of 1200 ppm or lower to protect the health and comfort of the occupants (Ministry of Education, 2017).

FIGURE 2.6: *School Indoor Air Quality and Ventilation: CO₂ Levels, Ventilation Rates, and Corresponding Effects on Student Performance and Health 2017*



Source: DQLS Indoor Air Quality and Thermal Comfort V1, Sept 2017

- Post-COVID-19

1. **WHO Temperature Range:** No changes were made.
2. **ASHRAE Relative Humidity Range:** No changes were made except to issue more detailed guidance on increasing ventilation rates.
3. **NZ guidance:** There is a stronger focus on maintaining CO₂ levels **well below the 1000 ppm**, as indicated in **Figure 2.7** threshold to ensure better ventilation and air quality as set by MoE (Ministry of Education, 2023).

FIGURE 2.7: School Indoor Air Quality and Ventilation: CO₂ Levels, Ventilation Rates, and Corresponding Effects on Student Performance and Health 2022

SCHOOL INDOOR AIR QUALITY & VENTILATION															
SEASON	SUMMER							WINTER							
	SUMMER RANGE							WINTER RANGE							
DOLS PERFORMANCE REQUIREMENTS	<800 PPM ON DEMAND							1250 PPM AVERAGE							2000 PPM MAXIMUM
INDOOR CO2 LEVEL PPM	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000	
VENTILATION EFFECTIVENESS	OUTSIDE AIR		WELL VENTILATED		IDEAL		UNDER VENTILATED			POORLY VENTILATED					
OUTDOOR AIR CHANGE / HOUR	10 ACPH		7.5 ACPH	5 ACPH	4 ACPH	3 ACPH		2.5 ACPH		2 ACPH		1.25 ACPH		0.75 ACPH	
OUTDOOR AIR L / S / PERSON	20 L/S		15 L/S	10 L/S	8 L/S	6 L/S		5 L/S		4 L/S		2.5 L/S		1.5 L/S	
SUBJECTIVE RESPONSE	FRESH				ODOURS				ODOURS AND STUFFINESS			ODOURS, STUFFINESS, HEADACHES AND FATIGUE			
INDICATIVE EFFECT ON NORMALIZED STUDENT PERFORMANCE	110% 105%				100%				95%			90%			
INDICATIVE EFFECT ON TOTAL SCHOOL ABSENCE	5%								15%						

Source: DQLS Indoor Air Quality and Thermal Comfort V2, Sept 2022

2.5.6 Applicability of regulatory documents to classrooms

The applicability of existing thermal comfort standards in educational settings has been challenged by various researchers (e.g., Mors et al., 2011; Teli et al., 2012, 2017). In their study, Teli et al. (2017) conducted a comparative analysis of the typical characteristics found in climate-controlled chambers, office buildings, university classrooms, and schools.

Their investigation focused on the disparate thermal environments and occupancy patterns observed in school classrooms. The authors emphasise that real-world settings often diverge significantly from the conditions in climate chambers. Furthermore, Teli et al. (2017) highlighted that a typical school day encompasses a range of activities within densely populated classrooms. Students have limited adaptive options and struggle to regulate the thermal conditions of their learning environment. Moreover, including outdoor recess periods at least twice a day for

schoolchildren contrasts sharply with adults' predominantly indoor occupancy profile in office settings.

2.5.7 Summary of regulations and guidelines

In summary, ASHRAE Standard 62.1, revised in 2019 and 2022, sets ventilation requirements for healthy indoor environments in buildings, including schools. It focusses on adequate ventilation rates to manage air contaminants and create comfortable spaces critical to student and staff health and performance. The standard specifies minimum outdoor air ventilation rates based on occupancy and function, ensuring adequate air quality for various school activities. In addition, it offers guidance on operational practices to maintain long-term IAQ and system effectiveness, balancing occupant health with energy efficiency. A notable recommendation from the standard is a standard classroom ventilation rate of 8 L/s.p, serving as a benchmark for designing ventilation systems in schools (ASHRAE, 2022a). However, the relationship between NZ Building Code Clause G4 and the NZ Standard for Ventilation and Air Quality (NZS 4303, 1990) highlights the adaptation of international standards to local conditions. Despite the current NZS4303:1990 aligning with the ASHRAE 62:1989 version, it has not been updated to more recent international standards like ASHRAE 62.1-2013 or 62.1-2022. The MoE's DQLS series provides sector-specific guidelines for educational environments, potentially addressing the gaps in the older NZ standard. The dual system approach of the general standard supplemented by sector-specific guidelines presents a flexible way to maintain up-to-date regulations without frequent revisions of the broader standard. However, potential inconsistencies and stakeholder confusion may arise when navigating multiple guidelines and standards within the educational sector. The applicability of existing TC standards in classrooms has been questioned due to the unique thermal environments and occupancy patterns observed in school settings, emphasising the need for customised approaches to address the specific requirements of educational spaces.

2.6 The combined effects of thermal conditions and ventilation on child health: Implications for IEQ

2.6.1 A brief overview

Research on IEQ takes a comprehensive approach, considering the interconnection of factors of IAQ and the implications for health. Understanding this broader context underscores the importance of effective IEQ management to maintain healthy indoor environments for living, teaching, and working. Poor IEQ can exacerbate respiratory conditions, spread diseases, and pose risks to cardiovascular, neurological, and cognitive health, highlighting the critical need for clean indoor air to prevent health problems (Ghosh et al., 2022; Kephelopoulos et al., 2014; UNICEF, 2019; World Health Organization et al., 1990).

Individuals with asthma, a major health concern in NZ, are particularly sensitive to air quality. NZ ranks high globally in asthma prevalence, with Māori and Pacific populations facing higher hospitalisation rates due to asthma-related issues. These disparities underscore the health inequities across ethnic and socioeconomic lines in NZ. Lower-income communities, particularly Māori and Pacific populations, face more significant challenges in coping with and escaping the health impacts of air pollution due to economic disparities, intensifying their vulnerability to poor air quality (Beasley et al., 2020; Borman et al., 2022; B. Du et al., 2020).

2.6.2 Epidemiological studies linking IEQ to specific health outcomes in primary school children

Vulnerable populations, such as children and older people, are a key focus of IEQ studies. Children, in particular, are highly susceptible to poor IEQ due to their higher metabolic rates, substantial oxygen demand, and increased ventilation needs (Kakoulli et al., 2022; 2023; Toyinbo, 2023). Inferior IEQ can lead to various health issues, from headaches to cognitive impacts and academic performance. Research by Sunyer et al. (2015) highlights the adverse effects of traffic-related air pollution on children's cognitive development, while Mendell et al. (2013) demonstrate the positive impact of higher classroom ventilation rates on student health and attendance. This emphasises the importance of maintaining optimal IEQ, especially in educational settings, to safeguard vulnerable populations' well-being

and academic outcomes.

Epidemiological research has revealed a significant link between IEQ in school classrooms and a spectrum of health and academic outcomes in primary school children. The key findings highlight the following areas:

- **Respiratory health:** Poor IAQ is a factor in the increased incidence of respiratory problems in children, such as asthma, respiratory infections, and allergic rhinitis. Exposure to classroom air pollutants, including VOCs, PM, and allergens such as dust mites and mould, has been consistently associated with these detrimental health outcomes (Beasley et al., 2020).
- **Academic and cognitive performance:** Improved IAQ has been associated with better focus, reduced absenteeism, and greater academic success. Elevated CO₂, often indicative of inadequate ventilation, can lead to decreased alertness and slower cognitive processing, affecting student learning capabilities (Taylor et al., 2016; X. Zhang et al., 2017).
- **Sick building syndrome (SBS):** Symptoms of SBS, such as headaches, fatigue, and concentration problems that improve after leaving the classroom, underscore the role that potentially harmful indoor air pollutants play in the school setting (Fernández-Agüera et al., 2019; Raju et al., 2020).

In response to these findings, interventions to improve IAQ in schools are being pursued, including upgrading HVAC systems, opting for construction materials with lower VOC emissions, maintaining the facility to address issues such as mould, and instituting policies to reduce exposure to external pollutants (Vasile et al., 2024; Zhu et al., 2024). These efforts are essential to foster healthier and more conducive learning environments for children.

2.6.3 Summary of health effects of TC&V

The research on IEQ emphasises the importance of considering the interconnection of IAQ factors and their impact on health. Poor IEQ can exacerbate respiratory conditions, spread diseases, and pose risks to cardiovascular, neurological, and cognitive health, particularly affecting vulnerable populations such as children. Studies have shown that maintaining optimal IEQ in educational settings is crucial to safeguarding the well-being of primary school children and academic outcomes.

Poor IAQ in classrooms has been associated with respiratory problems, reduced academic performance, and SBS symptoms. Interventions to improve IAQ in schools, such as upgrading HVAC systems and reducing exposure to pollutants, are essential for creating healthier and more conducive learning environments. Addressing IEQ issues is vital to preventing health problems and promoting overall well-being in indoor spaces.

2.7 IEQ in primary school classrooms - International context

Understanding the global dynamics of IEQ in primary school classrooms requires a review of international studies focussing on CO₂ levels, temperature, and RH as indicators of air quality. Although acknowledging extensive research in this field, this segment **selectively examines key studies to highlight trends** and emphasise the importance of creating optimal classroom conditions for educational success. This curated approach sets the stage for more detailed exploration in subsequent sections, reinforcing the relevance and urgency of the research.

2.7.1 CO₂, temperature and relative humidity

For readers looking for a detailed quantitative overview of the specific levels of CO₂, temperature, and HR examined in the research context, these metrics have been compiled and can be found consolidated in **Table 2.6, 2.7 and 2.8.**

TABLE 2.6: Summary of General CO₂, temperature and RH Studies

Author	Location of study	Participant No.	IEQ Conditions
Auliciems, 1972	England, UK	2500 assessments	1. Optimum performance temps for school children "comfortably cool" range between 14.7 °C and 16.7 °C.
Diaz et al., 2021	Chile	S=8 C=16	1. CO ₂ above 1400 ppm most of the time. 2. CO ₂ can reach peaks of 5000 ppm during the day, especially in winter. 3. Ave temp ranged from 9.9 °C to 32.2 °C, with lowest temps in Santiago in winter and highest in Puerto Montt during spring. 4. RH readings ranged from 5% to 98%, with ave of 49.7% in Puerto Montt and 53.8% in Santiago.
Dorizas et al., 2015	Athens, Greece	S=9	1. Median temp of 22.3 °C correlated with total satisfaction. 2. Temps exceeding 25 °C led to total dissatisfaction.
Fromme et al., 2008	Bavaria, Germany	S=75 C=92	1. Median CO ₂ concentrations ranged from 598 to 4172 ppm in winter and 480 to 1875 ppm in summer. 2. In winter, 92% of classrooms had levels above 1000 ppm, while in summer, only 28% of classrooms had increase concentrations.
Gaihre et al., 2014	Aberdeen, Scotland	S=30 C=60	1. Median CO ₂ 1086 ppm. 2. Time where CO ₂ concentrations exceeded 1000 ppm was 45 minutes.
J. Kim and de Dear, 2018	New South Wales, Australia	3545 students	1. 88.4% of samples fell within the 80% acceptability range, with only 2.7% of room temps exceeding upper limit and 8.9% below the lower limit.
Liang et al., 2012	Taichung, Taiwan	C=48 1614 students	1. Neutral temp (tn) for students in hottest month was recorded at 29.2 °C which is 2.3 °C higher than ASHRAE Standard 55 suggester level of 26.9 °C. 2. In coldest month tn was 22.4 °C, closely aligning with ASHRAE Standard 55 recommendation of 23.0 °C. 3. Mean monthly indoor operative temps varied significantly, max temps reaching 33.8 °C in classrooms.
Ma et al., 2020	Shenyang, China	C=4 141 students	1. Field measurements revealed that indoor temperatures ranged from 17.06 to 24.29 °C, with 2. CO ₂ levels between 1701 and 3959 ppm. 3. RH in the classrooms ranged from 27.26% to 64.47%, with an average of 44.42%.
Mors et al., 2011	Netherlands	79 students	1. RH in classrooms ranged between 20% and 50%. 2. Temps ranged between 10 to 30 °C.
Sadrizadeh et al., 2022	Taiwan	-	1. Neutral temps for pupils in hottest month was approx 29.2 °C, which is higher than ASHRAE Standard 55. 2. A temperature of 22.3 °C was reported to make pupils feel satisfied, while temperatures above 25 °C led to dissatisfaction.

S = School, C = Classroom

TABLE 2.7: Summary of General CO₂, temperature and RH Studies continued

Author	Location of study	Participant No.	IEQ Conditions
Telejko and Zender-Świercz, 2017	Poland	S=6	1. Max CO₂ recorded concentration in classrooms exceeded 4000 ppm. 2. After modifications, max concentrations reduced to 950 ppm. 3. Temp in classrooms ranged from 22 to 24 °C. 4. After modifications, temp decreased by approx. 3°C. 5. RH ranged from 33 to 45%. 6. Values increased slightly after modifications.
Wargocki and Wyon, 2006	Denmark	Sample size not detailed	1. CO₂ ranged from 600 to 3800 ppm in classrooms. 2. Performance in reading and maths tests decreased by 30% at 27 °C compared to 20 °C. 3. Ave temps were manipulated to 20 °C and 23.6 °C for different experiment conditions. 4. Performance was approx 5.7% better at classroom temp of 22.5 °C compared to 26 °C.
Wargocki and Wyon, 2007a	Denmark	48 participants	1. Performance was significantly lower at 27 °C compared to 20 °C. 2. Reducing temps from 25 °C to 20 °C significantly improved (numerical and language) tests. 3. Experiment manipulated temps at 20 °C, 27 °C and 30 °C.
Wargocki and Wyon, 2007b	Zealand, Denmark	Sample size not detailed	1. Ave CO₂ concentration reduced from 1300 to 900 ppm with increased outdoor air supply. 2. CO₂ concentrations remained higher at low ventilation rates, despite longer window openings. 3. Temp approx 19 °C.
Wargocki, 2022	California, USA	2740 students	1. CO₂ concentrations ranged from 600 to 2100 ppm. 2. Temps varied from 25 °C at higher ventilation rates to 28 °C at lower rates.
Wyon et al., 1979	Climate chamber	72 participants (aged 17)	1. Participants exposed to rising temperatures - 20-29 °C.

S = School, C = Classroom

TABLE 2.8: *Summary of General CO₂, temperature and RH Studies continued*

Author	Location of study	Participant No.	IEQ Conditions
Zapata-Lancaster et al., 2023	South Wales, UK	S=2 C=6	1. Autumn (S=B) CO₂ between 500 ppm and 800 ppm. 2. Winter (S=B Classrooms 2 &3) CO₂ under 1200 ppm, while Classroom 1 had average levels around 700 ppm. 3. Spring and summer (S=B) mostly under 800 ppm, with peak of 1000 ppm in Classroom 3 during one morning in spring. 4. S=B C1 & C3 within recommended temp of 19-21 °C, while C=2 slightly colder at 18 °C during occupied times. 5. During winter S=B C1 maintained ave temp of 19 °C, aligning with recommendations, while C2 & C3 were slightly colder. 6. In S=A, during coldest period in spring 2022, ave temp ranged from min of 13 °C at 09:00 to max of 16 °C at 15:00. 7. In hottest period in Sumer 2022 for S=A, ave temp ranged from min 20 °C at 09:00 to max of 22 °C at 13:00. 8. Average hourly RH readings of the 6 monitored classrooms remained between 40% and 60% in autumn and winter seasons. 9. The RH readings were in alignments with CIBSE Guide A recommendations.
Y. Zhang et al., 2016	UK	S=30 C=203	1. 31% of classrooms did not meet proposed CO₂ level standards. 2. Levels were measured but specific readings not provided. 3. Average temp in heating season was 20.2 °C and 22.2 °C in non-heating season. 4. No overheating problems found in classrooms. 5. RH readings ranged from 35% to 70%, indicating no significant seasonal effect.

S = School, C = Classroom

Thermal comfort studies

Indoor thermal conditions in classrooms significantly affect the well-being and performance of schoolchildren, who are more vulnerable to environmental factors than adults (Sadrizadeh et al., 2022; Wargocki and Wyon, 2007a). Differences in physical and physiological characteristics, such as surface area - mass ratios, sweating rates, metabolism, body temperature, and cardiac output, highlight the need for customised TC models (Glazier, 2014). For example, Dutch schoolchildren's

metabolic rates are lower than those of adults for similar activities, with senior primary school children having rates 10% lower than those specified for sedentary office work in ISO 7730 (ISO7730, 2005).

Despite variations, children generally prefer slightly cooler indoor climates compared to adults (Ter Mors et al., 2011; Trebilcock et al., 2014); studies also show that contextual factors, such as adjustments of clothing in response to indoor and outdoor temperatures, can influence comfort, although constraints such as uniform policies often limit these adaptations (J. Kim and de Dear, 2018; Sadrizadeh et al., 2022). For example, Sydney schoolchildren showed unchanged clothing insulation irrespective of temperature fluctuations due to school uniform norms.

Research confirms that children's optimal TC levels are lower than those of adults in the same thermal conditions, suggesting that students feel satisfied around 22.31 °C, but discomfort sets in above 25 °C (Dorizas et al., 2015; Haddad et al., 2017). In contrast, Taiwanese students reported neutral temperatures reaching 29.2 °C during the warmer months, exceeding some standards' recommendations (Liang et al., 2012).

Historically, research by Pepler and Warner (1968) at Kansas State University established that temperature-controlled classrooms improved student performance, showing significant variability in work speed and precision in a temperature range of 16 °C to 33 °C. Their findings revealed a 17% increase in accuracy but a decrease in speed when the temperature increased from 17 °C to 27 °C.

Wyon et al. (1979) highlighted that extreme temperatures hinder essential cognitive abilities for learning, noting that high school students could improve memory tasks up to 26 °C, with performance declining beyond this, particularly affecting male students. Similarly, Holmberg and Wyon (1969) found that higher classroom temperatures, at 27 °C and 30 °C, negatively impact reading speed and comprehension in children aged 9-12 years. Performance deterioration was more pronounced in the afternoons, likely due to increased fatigue. Their studies also indicated that younger children had difficulty adjusting their clothing to manage their TC, often leading to over-dressing and overheating.

Furthermore, further research by Holmberg and Wyon on Swedish and English children indicated that while Swedish children's performance declined at 27 °C, English children maintained their performance levels, suggesting that the threshold temperature affecting student performance varies with the climate context. Auliciems (1972) found optimal learning conditions for English secondary school students at around 16 °C, a comfortable cool state that boosted productivity.

Wargocki and Wyon (2007a; 2007b) demonstrated that slight temperature reductions in classrooms during warmer periods significantly enhance academic performance. In Danish schools, lowering classroom temperatures from 25 °C to 20 °C improved students' speed on numerical and language-related tests without increasing errors. Furthermore, a study by Wargocki and Wyon (2006) showed that a 1 °C reduction in classroom temperature could improve performance speed by 2%-4% on various tasks.

The research by Ito and Murakami (2010) in Japanese schools corroborated these findings, showing that the decrease in classroom temperatures from a baseline of 28 °C significantly improved academic performance, with performance enhancements of 26%, 43%, and 53% for 1 °C, 2 °C, and 3 °C reductions, respectively.

However, Klepeis' findings (as cited in Gaihre et al., 2014) suggested that no direct correlation was identified between indoor temperature, relative humidity, and student attendance or academic achievement, adding another layer to the nuanced understanding of the relationship between indoor climate and educational results.

Studies on TC in classrooms reveal that children have different physical and physiological needs compared to adults, highlighting the importance of maintaining optimal indoor temperatures slightly cooler than those suited for adults to improve comfort and learning outcomes.

General CO₂ temperature and RH studies

As early as 2008, Fromme et al. observed significant seasonal variations in IEQ, with classroom settings often failing to meet optimal CO₂ levels, especially in winter, highlighting the need for effective ventilation throughout the year (Fromme et al., 2008).

Gaihre (2014) highlighted that a mere 100 ppm increase in CO₂ could reduce student attendance by 0.2%, roughly half a day in a school year of 190 days (2014). Although academic performance was not directly affected by time-weighted average CO₂ concentrations - with mean levels at 1086 ppm, above the recommended 1000 ppm - the attendance effects were significant (2014).

Zhang (2016) reported that 31% of the UK's classrooms exceeded 1500 ppm CO₂, indicating inadequate ventilation that could alter learning and cognition.

In Poland, Telejko (2017) reported antiquated ventilation in schools that failed to manage high occupancy, with CO₂ levels reaching more than 4000 ppm. The proposed improvements reduced CO₂ to 950 ppm but increased the demands for heating energy.

Diaz (2021) identified high CO₂ in Chilean classrooms due to dense occupancy and poor ventilation, exacerbated by economic and regulatory shortcomings. This emphasises widespread air quality problems that need viable solutions, particularly in the colder months.

Wargocki (2022) emphasised maintaining CO₂ below 900 ppm to improve academic performance, recommending operable windows and CO₂ sensors to manage IEQ.

Zapata-Lancaster (2023) provided recent information on how environmental factors in classrooms meet seasonal standards. Adjustments were made for energy and TC, and although students generally felt comfortable, they occasionally reported discomfort due to extreme temperatures or air freshness. Classroom temperatures often did not meet comfort standards in winter but were more likely to comply in spring and summer (Zapata-Lancaster et al., 2023).

In December, students reported general comfort with temperatures, indicating some adaptability, although occasional extreme hot or cold sensations persisted. Students also perceived good air freshness in winter, despite potentially higher CO₂ concentrations due to reduced ventilation, reflecting subjective comfort rather than actual CO₂ levels.

Teachers in South Wales maintained a neutral position on classroom temperature and air quality, possibly indicating satisfactory conditions, adaptation, or a disconnect between their perceptions and optimal student environments (2023).

Zapata-Lancaster (2023) enriches our understanding of student and teacher responses to indoor classroom climates, stressing the delicate balance between TC, energy efficiency, and air quality for optimal learning environments.

These studies highlight the widespread issue of maintaining low CO₂ levels in educational settings, reflecting the need for better ventilation systems. Continuous academic discourse reveals the persistent challenge of elevated CO₂ in various regions, underscoring the significant impact of environmental conditions, such as CO₂ levels, temperature and HR, on student well-being and academic outcomes.

Energy efficiency and air tightness studies

Table 2.9 summarises the literature reviewed in this section.

TABLE 2.9: *Summary of Energy Efficiency and Air Tightness Studies, by date*

Author	Location of study	No. of Participants (Schools & Classrooms)	IEQ Conditions
Mainka, 2018	Poland	S = 2	1. The ave CO₂ concentrations in the thermally improved school ranged from 1287 ±333 ppm to 2146 ±386 ppm. 2. The ave concentrations in the school without thermal improvement ranged from 936 ±196 ppm to 1878 ±567 ppm. 3. This means that in the school that had improvements to keep heat in, there was more CO₂ in the air than in the older school building.
Ma, 2022	Shenyang, China.	C = 4	1. CO₂ ranged from 1701 to 3959 ppm. 2. Ranged from 17.06 to 24.29 °C. 3. The thermal neutral temperature was 18.5 °C. 4. 57% of the indoor RH values during the school period were less than 45%.

Over time, the discussions expanded to cover the implications of energy efficiency measures in school buildings. Mainka (2018) found that school thermal upgrades increased CO₂ levels due to improved insulation and reduced natural air exchange. In contrast, Ma (2020) observed that students in cold regions of China preferred cooler classroom temperatures, calling for customised air quality systems and

research into child-centric comfort standards. These studies highlight the common issue of high CO₂ levels in classrooms, highlighting the need for improvements in ventilation and design adjustments to balance air quality with energy efficiency. In general, inadequate classroom ventilation, especially during colder periods, negatively impacts student well-being and attendance, highlighting the importance of improving ventilation strategies while considering energy efficiency.

2.7.2 Ventilation rate studies

Table 2.10 summarises the findings of the ventilation studies, with implications discussed later.

TABLE 2.10: *Summary of Ventilation Rate Studies*

Author	Location of study	No. of Participants (Schools & Classrooms)	IEQ Conditions
Bako-Biro, 2007	UK	S = 1 C = 2	Ventilation rates increased from 0.3-0.5 L/s.p to 13-16 L/s.p as a result of the intervention using a direct air supply system through the windows.
Canha et al., 2013	Finland & Portugal	S = 4	1. Finland - mechanical ventilation = average 13.3 L/s.p, but one classroom had a lower rate of 7.2 L/s.p 2. Portugal - natural ventilation = average 2.4 L/s.p 3. Weekly ave CO₂ levels during classes ranged from 1286 to 5546 ppm (median 2776 ppm). 4. CO₂ levels were substantially above existing national and international guidelines. 5. Ave classroom temperatures during lessons varied from 9.1 °C to 14.4 °C (median 11.7 °C). 6. Indoor temperature in most classrooms was below the commonly recommended levels.

CO₂ levels are a proxy for ventilation adequacy in indoor spaces, as CO₂ is a byproduct of human respiration. Effective ventilation systems dilute and remove CO₂, ensuring fresh air replacement and maintaining low indoor CO₂ concentrations (Park and Song, 2023). A higher air exchange rate reflects more efficient CO₂ removal and better ventilation. Insufficient ventilation can lead to high CO₂ levels, resulting in symptoms like headaches, drowsiness, and reduced cognitive functions (Bassett and Gibson, 1999; Thörn, 1999). Guidelines often recommend keeping CO₂ levels below 1,000 ppm to ensure a healthy indoor environment (ASHRAE, 2020; Fullbrook et al., 2022). Monitoring CO₂ is an effective indicator of the improvement needs in

ventilation efficiency and IAQ.

Bakó-Biró (2007) improved classroom ventilation by installing direct air supply systems in window units, significantly increasing air delivery from 0.3 to 0.5 L/s.p to 13 to 16 L/s.p (Bakó-Biró et al., 2007). This upgrade led to an average increase in student productivity 7%, highlighting the link between better ventilation and cognitive performance, especially in concentration tasks such as arithmetic (Bakó-Biró et al., 2007). The findings suggest that investing in effective ventilation systems can improve educational outcomes, although they are based on data from a single school (Bakó-Biró et al., 2007).

Canha et al. (2013) found that most Finnish primary schools with mechanical ventilation achieved an average rate of 13.3 L/s.p, exceeding the recommendations of the health authority. However, a Finnish classroom had a lower rate of 7.2 L/s.p and CO₂ levels that occasionally exceeded 1200 ppm, indicating a suboptimal air quality. In contrast, Portuguese classrooms relying on natural ventilation had average rates of just 2.4 L/s.p, signalling poor air quality. Portuguese schools experienced even less air flow during the colder months, exacerbating poor indoor conditions (Canha et al., 2013). Although Finnish classrooms with mechanical systems generally met the standards throughout the year, some still had elevated CO₂ levels, suggesting that ventilation rate benchmarks do not always ensure optimal air quality (Canha et al., 2013). These results emphasise the need for better school ventilation strategies that rely on natural airflow to promote a healthy indoor environment and student well-being (Canha et al., 2013).

From the cited research, the following conclusions can be drawn:

- **Improved ventilation boosts cognitive performance:** Upgrading classroom ventilation to deliver 13-16 L/s.p per person, compared to the insufficient 0.3-0.5 L/s.p, resulted in a significant 7% increase in student productivity, highlighting the link between better air quality and cognitive functions (Bakó-Biró et al., 2007).
- **Educational benefits from enhanced ventilation systems:** Proper ventilation is essential in academic settings, improving cognitive engagement and productivity. Investing in efficient school ventilation infrastructure improves learning outcomes (Bakó-Biró et al., 2007).

- **Consistency in ventilation rates is critical:** Most Finnish schools with mechanical ventilation met the recommended 13.3 L/s.p rate. However, deviations, such as a classroom with only 7.2 L/s.p and CO₂ levels over 1200 ppm, indicate that an average rate alone does not ensure optimal air quality. Suitable and consistent ventilation in all spaces is necessary (Canha et al., 2013).
- **Natural ventilation systems may be inadequate:** Portuguese classrooms relying on natural ventilation averaged only 2.4 L/s.p, often dropping lower during Winter, leading to poor air conditions. This suggests a need for additional mechanical ventilation or other strategies to ensure a healthy IAQ (Canha et al., 2013).
- **Ventilation rates alone do not ensure air quality:** In Finnish classrooms with mechanical systems that meet the recommended rates, sporadic high CO₂ levels were recorded, indicating that the ventilation rate is not the only determinant of air quality. Other factors must be managed to maintain consistent IAQ (Canha et al., 2013).
- **Prioritising school ventilation enhances health and learning:** Both studies indicate school authorities need to implement effective ventilation strategies. Ensuring good ventilation supports health and cognitive performance, possibly requiring policy changes or investments when current systems are inadequate (Canha et al., 2013).

Studies highlight the importance of maintaining adequate ventilation rates in school classrooms to ensure low CO₂ levels, which are crucial to both air quality and cognitive performance, highlighting that while mechanical systems generally provide better ventilation than natural methods, consistency in maintaining recommended air exchange rates is essential for optimal indoor environments.

2.7.3 Impact of SARS-CoV-2 on ventilation

The COVID-19 pandemic has intensified the focus on IEQ and ventilation, given their critical role in reducing viral transmission risks in shared indoor spaces like schools. Understanding the impact of ventilation on the control of airborne infections has become essential for public health. This section reviews relevant studies on IEQ and ventilation during the pandemic. **Table 2.11** summarises these studies, providing an overview of their findings, which will be discussed in detail. These insights highlight

the importance of ventilation in maintaining air quality and controlling infections, contributing to the narrative on adaptive environmental health practices necessary to protect public well-being during airborne disease outbreaks.

Gohara (2022) measured CO₂ levels in a Tokyo elementary school to assess the impact of the COVID-19 pandemic on classroom ventilation. Before the pandemic, the average air change rate, a measure of air circulation efficiency, was 1.4 ACpH in summer 2019, dropping to 1.0 ACpH in winter (Gohara et al., 2022). With health and safety measures during the pandemic, these rates increased significantly to 6.3 ACpH in the summer of 2020 and remained high at 6.0 ACpH in winter (Gohara et al., 2022). The rise was due to frequent window openings to reduce viral spread, allowing greater airflow and faster CO₂ outflow (Gohara et al., 2022). The study highlights that simple opening of windows can significantly improve ventilation, essential for maintaining air quality and reducing CO₂ levels, benefiting students and teachers (Gohara et al., 2022).

Alonso (2021) demonstrated that the combination of natural and mechanical ventilation in schools significantly reduced CO₂ levels by an average of 300 ppm per week, with a marked decrease of 400 ppm from natural ventilation, such as opening windows and doors (Alonso et al., 2021). These measures improved air quality during the pandemic. However, during winter, this approach made the classrooms uncomfortable for 60% of the time (Alonso et al., 2021). The study highlights the need to balance improving air quality to prevent virus spread and maintaining a comfortable learning environment, as extreme temperatures can affect student comfort and concentration (Alonso et al., 2021).

Kulo (2021) studied the impact of pandemic-related ventilation measures on classroom air quality during the colder months. Despite reduced class sizes and more frequent ventilation, some classrooms still did not meet cleanliness standards, with higher than recommended levels of fine particles and CO₂, particularly where windows were rarely opened (Kulo et al., 2021). Classroom temperatures and RH levels also often did not meet optimal learning conditions.

TABLE 2.11: Summary of SARS-CoV-2 studies

Authors	Year	Location of study	No of Participants (Schools & Classrooms)	Ventilation rates	CO2 (ppm)	Temp (°C)	RH (%)
Gohara	2020	Tokyo		* Summer of 2019, average air change rate in the classrooms, was 1.4 times per hour. * Winter of 2019, it reduced to 1.0 times per hour. * During pandemic, the average air change rate increased significantly - Summer of 2020, it was 6.3 times per hour, and in the winter of 2020, it was 6.0 times per hour.			
Alonso	2021	Southern Spain	C = 2		* Weekly averages decreased by 300 ppm during the pandemic with hybrid ventilation. * Weekly averages decreased by 400 ppm during the pandemic with natural ventilation.		
Kulo	2021	Canton, Sarajevo	S = 4, C = 4		* Oct min - 705; max - 1443 * Nov min - 421; max - 1080 * Dec min - 752; max - 1003 * Jan min - 425; max - 657 * Feb min - 953; max - 2826	* Oct min - 24; max - 30 * Nov min - 22; max - 26 * Dec min - 22; max - 27 * Jan min - 15; max - 18 * Feb min - 22; max - 26	* Oct min - 35; max - 58 * Nov min - 37; max - 55 * Dec min - 30; max - 56 * Jan min - 54; max - 60 * Feb min - 23; max - 49
Zemitis	2021	Latvia	S = 14, C = 42		* Min 2380 ppm * Max 4424 ppm.		
Vignolo	2022	Uruguay	S = 1, C = 1	n/a	n/a		
Bain-Reguis	2022	Scotland	S = 4, C = 19	* Victorian schools had approx 4.38 L/s/p fresh air. * Newer buildings with natural ventilation did a bit better, with 5.8 L/s/p. * Classrooms with mechanical ventilation had approx 6.08 L/s/p.			
Burridge	2023	UK	S = 4, C = 36		* Warm weather CO2 levels were pretty good. * But when it got cold, the CO2 levels went up. * Near the end of 2021, the CO2 levels were even higher than at the start of the year, even though the classrooms and how they were used didn't change. This might mean that the way people were letting fresh air into the classrooms had changed.	n/a	

CO₂ levels generally stayed below the safe 1000 ppm threshold for 8 hours, but exceptions occurred. For example, School 4 exceeded the guidelines by 50% in October and recorded the highest CO₂ levels in February (Kulo et al., 2021). Smaller increases of up to 40% were observed in Schools 2 and 3 during February. During a specific 100-minute observation, CO₂ levels increased in all schools except School 1, where a decrease was observed after the first class. School 4 had the most concerning values, starting the third class with CO₂ levels up to 3.2 times the recommended limit.

School 2 had higher-than-ideal CO₂ levels by about 40%, but still lower than School 4. The lowest levels were in School 3, aided by continuous window ventilation, but even here, measurements exceeded the threshold by the end of the third class (Kulo et al., 2021). Despite increased ventilation efforts, the study underscores the challenges of maintaining air quality during the colder months.

Zemitis et al. (2021) observed significantly elevated CO₂ levels in classrooms, with an average of 2380 ppm and peaks reaching 4424 ppm. This indicates poor air quality and insufficient ventilation (Zemitis et al., 2021). The excessive CO₂ levels were attributed to COVID-19 safety protocols that kept the students in the same room all day without adequate ventilation (Zemitis et al., 2021). Although attempts were made to improve airflow by opening windows, these measures were inadequate. Furthermore, since students remained in the classroom during breaks, there were fewer opportunities for natural ventilation, leading to a steady accumulation of CO₂ (Zemitis et al., 2021).

Vignolo (2022) evaluated the effectiveness of natural ventilation in an elementary school by simulating fresh air exchange rates of 0.5, 1, 3.80, and 6.43 ACpH. The highest rate aligns with the ASHRAE 62.1 and WHO guidelines to mitigate airborne disease spread. The findings indicated that periodic window openings significantly reduce transmission risks and improve air quality without extensive infrastructure changes (Vignolo et al., 2022). The transition from winter to spring also helped reduce transmission risks.

Bain-Reguis (2022) evaluated the air quality in different ventilation systems through CO₂ monitoring. Mechanically ventilated classrooms exhibited better air quality than those with natural ventilation. Factors such as classroom occupancy and window openings impacted CO₂ levels; more open windows led to more effective CO₂

reduction. The older NV buildings provided about 4.38 L/s.p of fresh air, slightly improving in the newer buildings to 5.8 L/s.p. Mechanical systems outperformed both, offering around 6.08 L/s.p (Bain-Reguis et al., 2022). Proper ventilation is essential for health and safety, particularly during the COVID-19 pandemic, when it helps mitigate viral transmission.

Burridge et al. (2023) examined CO₂ levels in 36 classrooms in four UK schools in 2021, focussing on schools without air conditioning. CO₂ levels were acceptable in warmer periods, but increased as temperatures decreased, indicating a reduced intake of fresh air (Burridge et al., 2023). Higher CO₂ levels were observed towards the end of 2021 despite unchanged classroom usage, suggesting altered ventilation practices. Variations in CO₂ readings across different schools and classrooms highlighted the influence of specific ventilation practices on air quality. The study highlights the importance of evaluating individual classroom ventilation and the impact of human behaviours on air circulation. It calls for a further investigation into fresh air management in UK schools to ensure optimal learning environments (Burridge et al., 2023).

In summary, the aforementioned studies collectively highlight the role of effective ventilation in classrooms during the COVID-19 pandemic.

- Gohara's (2022) research observed a marked increase in air change rates in a Tokyo school, reflecting increased ventilation efforts in response to the health crisis. The significant increase from pre-pandemic levels highlights the adaptation of schools to the pandemic's demands for improved air circulation.
- However, Alonso's (2021) study highlights a consequent issue: the increased air exchange rates, while reducing CO₂ levels, also led to thermal discomfort due to colder temperatures, affecting more than 60% of the classrooms.
- Kulo's (2021) findings mirror this concern, indicating that IAQ often did not meet standards despite more frequent ventilation and smaller class sizes, particularly when natural ventilation was solely relied upon and windows were seldom opened.
- Zemitis et al. (2021) also reported worrying CO₂ levels, far exceeding the recommended safe thresholds, pointing to inadequate ventilation measures even when windows were opened. This persistent issue indicates that simply

opening windows is not always sufficient to maintain a healthy indoor atmosphere.

- Vignolo (2022) found that periodic windows opening could effectively manage the risk of disease transmission and suggested that it is beneficial to maintain air quality and TC, showcasing an effective and unobtrusive ventilation strategy.
- Bain-Reguis (2022) illustrated the variance in air quality based on ventilation systems, with mechanically ventilated classrooms typically displaying better air quality than those with natural ventilation. The study calls for improving natural ventilation to ensure satisfactory air exchange and comfort.
- Burridge et al. (2023) reported that while CO₂ levels remained acceptable during warmer months, reflecting sufficient ventilation, levels rose in cooler periods, suggesting reduced airflow and potential discomfort due to increased classroom stuffiness.

2.7.4 Summary of international context

Overall, the synthesis of these studies points to the need to optimise IEQ through natural and mechanical ventilation to protect health while considering comfort during varying climatic conditions. This highlights the complexity of managing school ventilation and the importance of tailored solutions to maintain safety and comfort.

The collected studies emphasise the critical importance of optimising ventilation in school classrooms during the COVID-19 pandemic, revealing that increased ventilation efforts effectively reduce CO₂ levels and infection risks, but also highlight challenges such as maintaining TC and consistent air quality, especially during the colder months when natural ventilation may be insufficient.

2.8 IEQ in primary school classrooms - NZ context

Building on the comprehension of IEQ in educational settings, the focus is narrowed to the context of NZ. The PI will examine studies on CO₂ levels, temperature, and RH in primary school classrooms in NZ. The key studies, highlighted in green **Table 2.12**, are central to this discussion and summarised in **Table 2.13**, which maps the NZ research landscape.

TABLE 2.12: NZ IEQ studies

	Data Collected/Surveyed														Location		Region		
	ACH Rates	Bacterial Sampling	Metabolically generated CO2	Black Carbon	Energy Consumption	Formaldehyde	Fungi Sampling	Noise Levels	Particulate Matter	Pure CO2	Relative Humidity	School Building Sampling	Temperature	Total Suspended Particulates	TVOCs	Ventilation Rates		Experimental Chamber	Field Study
Bassett, 1999																			Wellington
Cutler-Welsh, 2006																			Christchurch
McIntosh, 2011																			Wellington
Trompetter, 2018																			
Bennett, 2019																			
NIWA, 2022																			Invercargill, Taupo, Wellington
Ackley, 2022																			
Wang, 2022																			Palmerston North
MoE, 2022																			Various locations

This review emphasises findings relevant to NZ's unique climate and educational settings. By assessing these studies, the PI aims to provide informed perspectives addressing NZ primary schools' specific needs and challenges, ensuring that the analysis is both relevant and actionable.

TABLE 2.13: *Expansion on Parameters of NZ IEQ Studies*

Author	Location of study	No. of Participants (Schools & Classrooms)	Duration & Season	IEQ Conditions – Ventilation rates (ACpH); CO ₂ (ppm); Temp (°C); RH (%)
Bassett and Gibson, 1999	Wellington	S = 12 C = 24	5 winter days	CO ₂ : Min = 651; Max = 1332; Ave = 994
Cutler-Welsh, 2006	Christchurch	S = 1	3 winter days	CO ₂ and Temp readings (07:00 – 16:00): Aug 7th – Max = 3222; Ave = 2417 and Outdoor temp = 9.4 Indoor temp = 17.7 Aug 14th – Max = 2805; Ave = 1358 and Outdoor temp = 7.1 Indoor temp = 16.4
McIntosh, 2011	Wellington	C = 57	Winter	CO ₂ : Min = 310; Max = 3935; Ave = 987.8; SD = 845.3 Temp: Min = 10.3; Max = 24.1; Ave = 18.7; SD = 3.8 RH: Min = 38; Max = 85; Ave = 56; SD = 11
BRANZ Report (Unpublished)	Auckland	C = 3	1 week in Winter & Spring	CO ₂ : A 100% < 1000; B 44% > 1500 Temp: Winter 20–25; Spring > 26 RH: 40–60
	Hawke's Bay	S = 2 C = 4	4 seasons	CO ₂ : Min = 739 (Spring); Max = 1988 (Summer) Temp: Min = 17.3 (Winter); Max = 24.2 (Summer) RH: Min = 48 (Spring); Max = 64 (Autumn)
	Christchurch	S = 4 C = 12		CO ₂ : Min = 452 (Winter); Max = 3789 (Autumn) Temp: Min = 9.4 (Winter); Max = 26.7 (Summer) RH: Min = 37 (Winter); Max = 81 (Winter)
	Dunedin	S = 4 C = 12		CO ₂ : Min = 459 (Autumn); Max = 1819 (Autumn) Temp: Min = 19.0 (Winter); Max = 24.1 (Summer) RH: Min = 36 (Spring); Max = 65 (Autumn)
Bennet et al., 2019	Wellington	C = 18	1 week in Winter	CO ₂ : Ave = 887; Min = 418; Max = 1626; SD = 271 Temp: Ave = 19.4; Min = 14.0; Max = 23.2; SD = 1.6
Wang, 2020	Palmerston North	S = 5 C = 20	4 seasons	ACpH: Min = 1.1; Max = 4.1 CO ₂ : Min = 710; Max = 2012 Temp: Min = 47.2; Max = 62.0 RH: Min = 47; Max = 62
NIWA, 2022	Invercargill, Taupo, Wellington	C = 3	5 summer days, Level 2 COVID-19	1. Natural ventilation different window layouts achieve between 0.7 – 1.7 ACpH 2. Exhaust fan increased ACpH from 3 to 12 and 12 to 22 (open doors and windows). Sealed room, four-fold increase in ACpH 0.7 – 3 3. CO ₂ – 31% time < 800 ppm; 36% time 800 – 1500 ppm; 31% time > 1500 ppm
Aniebiatabasi et al., 2022	Wellington	S = 3 C = 18	2 autumn weeks Gas cylinder used	ACpH: Min = 3; Max = 5

Bassett and Gibson (1999) monitored CO₂ levels in 18 classrooms over five days using a TSI non-dispersive infrared detector. The results revealed that CO₂ often exceeded the 1000 ppm limit for ventilated spaces. The levels peaked in the morning as the indoor temperatures approached 20 °C, but decreased when the windows were opened, stabilising the concentrations (Bassett and Gibson, 1999).

Cutler-Welsh (2006) highlighted ventilation concerns at Thorrington School, indicating elevated CO₂ levels in a classroom and ineffective use of heating resources. An energy audit by Meridian Energy in 2006 revealed misuse of heating equipment and excessive energy consumption. Furthermore, a heat recovery and ventilation (HRV) system vendor identified CO₂ levels that exceeded 3000 ppm in a classroom (Cutler-Welsh, 2006). The study suggested that the school may not meet the Ministry air turnover rate guideline of 8 L/s.p (Cutler-Welsh, 2006). Although the research proposed a climate management framework for classrooms, its scope was limited, raising questions about wider applicability and implementation challenges. However, the study emphasised the importance of energy conservation and the crucial role of school personnel in achieving long-term sustainability at Thorrington School (Cutler-Welsh, 2006).

McIntosh (2011) investigated IAQ in 35 primary schools in Wellington. Using portable TSI Q-Trak gas analyzers, CO₂ levels were monitored at five-minute intervals during occupied classroom hours in 2003 and 2005. The results indicated that 57% of the classrooms exceeded 1000 ppm of CO₂, with 9% exceeding 3000 ppm. Attempts to improve ventilation often led to uncomfortable temperature drops, affecting activities like reading and writing. The study highlighted concerns about thermal discomfort, with temperatures ranging from 10.3 °C to 24.1 °C and humidity levels between 38% and 85% (McIntosh, 2011). Low temperatures below 13 °C in nine classrooms increased health risks, according to the WHO. Occupation safety and health (OSH) guidelines regarding maintaining warmth for sedentary workers were cited. Despite teachers adapting to temperature fluctuations, student comfort was compromised, especially in lower socioeconomic schools. Some students lacked appropriate clothing for varying temperatures, and inadequate ventilation exacerbated these challenges. McIntosh emphasised that poor ventilation could contribute to student lethargy and discomfort.

Bennet et al. (2019) investigated the determinants of IAQ in primary school

classrooms, focussing on dust and fine particulates. Despite CO₂ levels and total dust count data not being highlighted in **Table 2.12**, they were deemed significant for inclusion due to limited local research. The study used the infiltration methodology, using CO₂ changes to assess airflow patterns. The findings indicated effective cross-ventilation when the classroom windows were open (Bennett et al., 2019).

During Wang's (2020) research, classroom temperature analysis in various schools revealed that most classrooms maintained optimal temperatures between 18 °C and 24 °C for most school hours. Although some classrooms experienced occasional dips below 16 °C, overall, temperatures were within the recommended range. However, exceptions were observed in specific classrooms where temperatures exceeded 24 °C, occasionally exceeding 28 °C, which could impact comfort levels (Y. Wang, 2020).

The patterns of heat exchange reflected a trend of activation during active school hours to ensure comfortable temperatures at the beginning of the day. The heaters were typically turned off once warmth was achieved, with reduced dependence in the afternoon due to sunlight and body heat. The daily use of the heater ranged from 1.1 to 3.2 hours, with unusual usage times observed (Y. Wang, 2020).

CO₂ concentrations in the studied schools generally remained below 800 ppm for most hours, but varied between classrooms and schools. Some classrooms experienced CO₂ levels within the 1000 to 1500 ppm range, while others peaked at 3000 to 5000 ppm. ACpH also showed significant variability, and most schools fell below the recommended four air changes per hour during winter (Y. Wang, 2020).

NIWA's rapid study (National Institute of Water and Atmospheric Research, 2022) highlighted classroom ventilation challenges, as rising CO₂ levels indicated inadequate air replacement. The variability in classroom ventilation practices highlighted the need for more research on air movement patterns in educational settings. Future studies should consider automated monitoring systems for a more precise ventilation assessment, particularly in tracking window and door usage (National Institute of Water and Atmospheric Research, 2022).

The study confirmed optimal air quality when opening doors and windows to establish crossflow, reducing CO₂ concentrations. However, inconsistent ventilation practices were observed, especially during mornings or due to external noise that

caused window closures. Partial openings were insufficient to achieve ideal air change rates, highlighting the need for full openings on multiple facades for effective natural ventilation (National Institute of Water and Atmospheric Research, 2022).

Despite the challenges in isolating the factors that contribute to effective ventilation, the study stressed the importance of strategic airflow management to maintain IAQ. External factors such as wind strength and temperature gradients were identified as possible influences on ventilation effectiveness, highlighting the need for adaptable ventilation strategies to address varying external conditions (National Institute of Water and Atmospheric Research, 2022).

Observations revealed that the full opening of multiple doors and windows to establish crossflow significantly reduced CO₂ levels, keeping concentrations below 800 ppm. The use of connections to larger unoccupied spaces through internal doors also helped decrease CO₂ levels by expanding the volume of dilution. Instances of poor ventilation, such as closed windows to mitigate external noise, highlighted the impact of external factors on indoor air exchange (National Institute of Water and Atmospheric Research, 2022).

Aniebietabasi (2022) found that achieving air change rates of 5 to 6 ACpH in classrooms often kept CO₂ levels below 800 ppm, indicating adequate ventilation (Sutherland et al., 2022). The study noted that opening the upper north and south windows halfway facilitated an air change rate of approximately 5 ACpH, demonstrating effective ventilation strategies (Aniebietabasi et al., 2022).

Manipulation of window openings significantly affected IAQ, with slight openings during colder weather, maintaining fresh air without causing excessive cooling. Rapid air replacement through expansive window and door openings, particularly during short breaks, proved beneficial to air circulation and crucial to reducing airborne disease transmission in shared environments such as schools (Aniebietabasi et al., 2022).

In a study by the MoE in 2022, examining 169 teaching spaces between May and August, CO₂ levels were mainly below 800 ppm, with temperatures within the optimal range of 18-25 °C for 70% of the time (Chen et al., 2022). However, teaching spaces in colder climates exhibited higher CO₂ levels, potentially due to inadequate

ventilation. The study suggested implementing scheduled "refresh breaks" at standardised times throughout the day to address persistent high CO₂ levels, promoting a healthier learning environment (Chen et al., 2022).

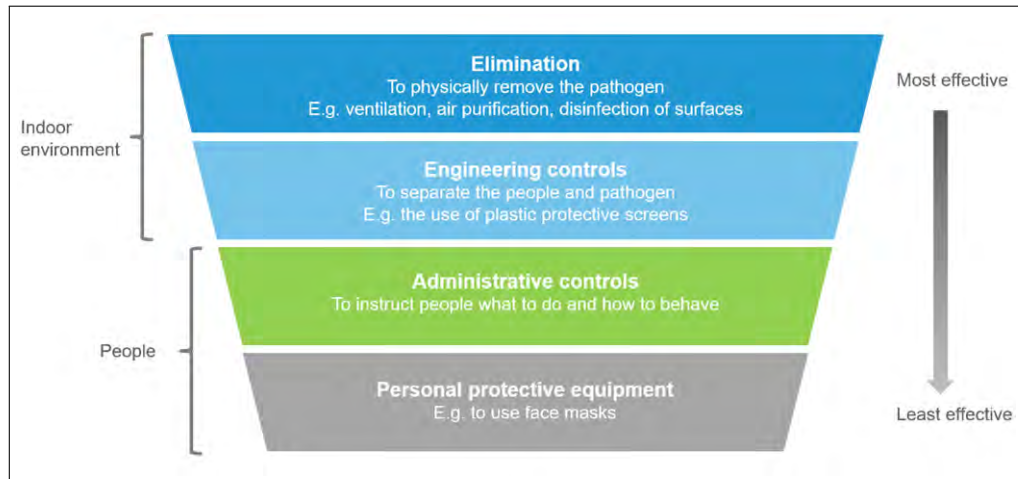
The studies highlight the challenges and importance of effective ventilation in NZ primary school classrooms, revealing elevated CO₂ levels due to inadequate natural ventilation and emphasise the need for a re-evaluation of ventilation standards, better energy management, and strategic use of windows and doors to improve air quality and ensure a conducive learning environment.

2.8.1 Impact of SARS-CoV-2 on NZ primary schools

Most NZ schools adhere to the MoE DQLS Guidelines, emphasising natural ventilation via openable windows. Compliance is necessary with the ventilation rates outlined in NZS4303:1990 and NZBC Clause G4 Ventilation (Standards New Zealand, 1990b). NZBC clause G4 mandates a minimum net openable window area of 5% of the combined habitable classroom floor area to achieve adequate ventilation (Standards New Zealand, 1990b). However, while schools meet design standards, no operational mechanisms guarantee that end-users consistently open windows.

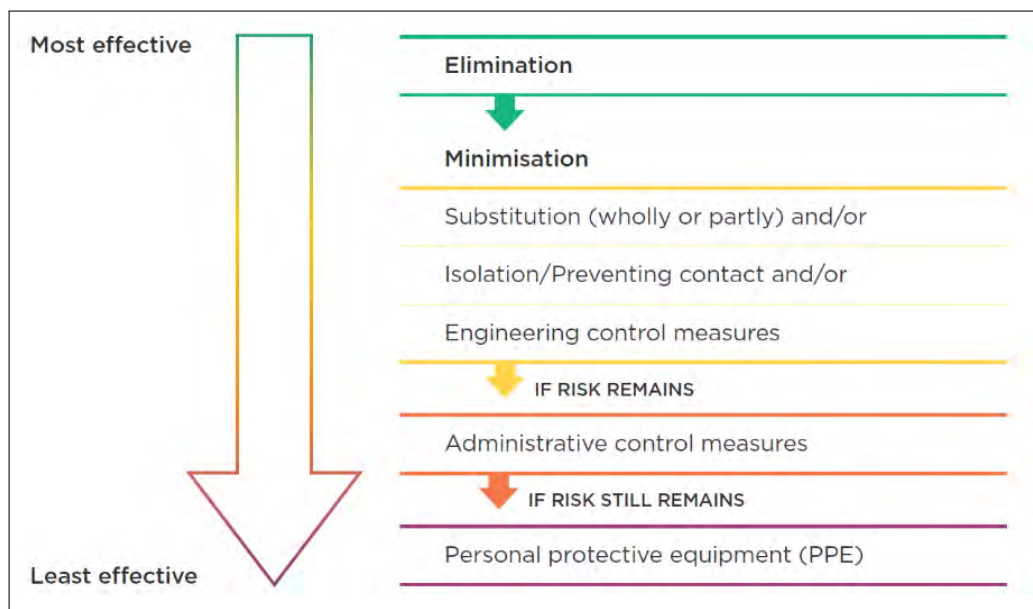
A study conducted in 40 Auckland (NZ) primary schools during the winter of 2015 revealed that only 40% of teachers open windows while teaching (Gully, 2015; Liaw, 2015). This percentage also decreased to 15% in a subsequent survey involving 33 teachers from nine schools in three NZ regions: Christchurch (N = 4), Dunedin (N = 3), and Hawke's Bay (N=2).

When considering the Centres for Disease Control and Prevention (CDC) infection control pyramid (**Figure 2.8**), pathogen elimination is the most effective measure, followed by engineering and administrative controls.

FIGURE 2.8: *Hierarchy of Controls for Pathogen Mitigation in Indoor Environments*

Source: adapted from Centers for Disease Control and Prevention, 2015

Personal protective equipment (PPE) is the least effective. According to Worksafe NZ, ventilation is considered a subset of elimination (**Figure 2.9**) and, again, is considered the most effective elimination method (Worksafe NZ, 2022).

FIGURE 2.9: *Hierarchy of Risk Controls for Workplace Safety*

Source: adapted from Worksafe Mahi Haumaru Aotearoa, 2022

In October 2021, the NZ MoE launched the COVID-19 Ventilation in Schools Response Programme (COVID-19 Ventilation Programme, or CVP). CVP aims

to reduce airborne transmission of SARS-CoV-2 by improving school ventilation strategies. One goal of this research was to repeat a previous survey to determine whether teachers' attitudes toward opening windows had changed. At the time of writing, the PI has not been able to verify the results of this report.

Despite NZ schools being designed for natural ventilation with open windows to meet building code requirements, surveys indicate low window opening rates by teachers, highlighting a disconnect between design intentions and actual classroom practices, which has led to initiatives such as the COVID-19 Ventilation Programme to address ventilation challenges and potential health impacts on students.

2.8.2 Summary of NZ context

In exploring IEQ within primary school classrooms in the NZ context, the PI delves into studies focussing on CO₂ levels and temperature and RH. Notable studies, detailed in Table 2.11, play a central role in this examination, summarised in Table 2.12, which delineates the NZ research landscape. These studies highlight findings pertinent to NZ's distinct climate and educational settings. By analysing these studies, the PI aims to offer insightful perspectives addressing NZ primary schools' specific requirements and obstacles, ensuring actionable insights. Highlighted studies include Bassett and Gibson (1999) monitoring CO₂ levels, Cutler-Welsh (2006) emphasising ventilation issues, McIntosh's (2011) IAQ investigation, Bennet et al. (2019) exploration of IAQ determinants, and Wang's (2020) research on classroom temperatures and ventilation practices. Additionally, NIWA's study (2022) underscores ventilation challenges and the significance of strategic airflow management. In contrast, Aniebietabasi (2022) found that achieving air change rates of 5 to 6 ACpH in classrooms often kept CO₂ levels below 800 ppm, indicating adequate ventilation (Chen et al., 2022). The study noted that opening the upper north and south windows halfway facilitated an air change rate of approximately 5 ACpH, demonstrating effective ventilation strategies (Aniebietabasi et al., 2022). Aniebietabasi's work (2022) indicates the effectiveness of achieving optimal air change rates. Furthermore, the NZ MoE study in 2022 revealed insights into CO₂ levels and temperature management in teaching spaces, emphasising the importance of addressing persistent high CO₂ levels for a healthier learning environment (Chen et al., 2022). The review of these studies sheds light on the criticality of effective ventilation in primary school classrooms in NZ, emphasising

the need to reassess ventilation standards, improved energy management, and strategic use of windows and doors to improve air quality and ensure conducive learning environments.

2.9 Pioneering studies and methodologies in IEQ research

Two key articles have significantly influenced the PI's research trajectory. The **SINPHONIE** project, funded by the European Union Executive Agency for Health and Consumers, aimed to improve air quality in schools and kindergartens to promote a healthy indoor environment for children (Baloch et al., 2020; Kephelopoulos et al., 2014). This extensive initiative collected empirical data on indoor air pollutants from 114 schools in 23 European countries, evaluating the impact on children's health and well-being (Annesi-Maesano et al., 2013; Baloch et al., 2020).

The SINPHONIE study focused on CO₂ levels, temperature and RH in classrooms in Nevada, relating elevated CO₂ concentrations with respiratory problems in students. Although most of the classrooms maintained temperatures between 20-25 °C, high CO₂ levels exceeding the 1000 ppm target, affecting student absenteeism and academic performance (Annesi-Maesano et al., 2013; Baloch et al., 2020). Furthermore, moisture presence indicators were associated with increased cases of RH and asthma among children, demonstrating the complex relationship between environmental factors and health outcomes (Annesi-Maesano et al., 2013).

The SINPHONIE project's findings have contributed to European human biomonitoring initiatives and evidence-based policies to improve school environments and safeguard children's health. The study highlights the importance of ongoing surveillance and interventions to improve indoor environmental conditions throughout Europe, focussing on environmental health in schools as a public health priority (Annesi-Maesano et al., 2013).

The **ICONE** index (air stuffiness index), originating from the EU-funded "Indoor Air Pollution in Schools" project led by the European Federation of Allergies and Airways Diseases Patients' Associations (EFA), was developed by the French

Scientific and Technical Center for Building (CSTB) to quantify air quality confines in classrooms (Michelot et al., 2012). The ICONE index is based on a calculation from continuous CO₂ concentration monitoring in an occupied classroom for at least one school week.

This initiative addresses ventilation issues that affect children with allergies and respiratory conditions, in order to improve understanding of how school environments affect the health of vulnerable individuals (Michelot et al., 2012). CSTB researchers noted that informing teachers about classroom air conditions led to adjustments in ventilation methods, reducing airborne pollutants and CO₂ levels to enhance air quality (Michelot et al., 2012).

The ICONE index provides a practical tool for evaluating and improving school air quality, emphasising the connection between indoor air pollution, cognitive function, and health. By empowering educators with measurable metrics, the index facilitates informed ventilation decisions to improve air renewal, reduce CO₂, and mitigate indoor pollutants, creating healthier learning environments for children (Michelot et al., 2012).

Although the ICONE index served as inspiration for the thesis, its calculation from the collected data was not included within the thesis itself due to word count limitations. An analysis incorporating the ICONE index is planned for a subsequent journal paper. Preliminary work with the index was carried out using data from the pilot study and these findings were presented at a conference in China (L. Tookey et al., 2019). This prior experience with the ICONE index strengthens the foundation for its application to the full dataset and its subsequent publication.

2.10 Window opening behaviour in primary school classrooms

Previous sections explored the multifaceted aspects that shape IEQ in educational settings, particularly focussing on factors such as TC, CO₂ levels, and ventilation. Shifting towards an analysis of behavioural influences on IEQ, the upcoming section will examine the practice of window opening—a seemingly routine yet impactful action. This investigation will explore the motivations driving these behaviours, the

impact on air change rates, and the consequent implications for classroom IEQ. The study illustrates how simple behaviours can notably alter the IEQ within classrooms by examining the dynamic between human actions and environmental parameters.

2.10.1 Impact of window opening behaviour on IEQ

The following studies have previously been summarised in Tables 2.6 and 2.7.

Ventilating classrooms by opening windows during the colder seasons presents a complex trade-off between air quality and TC. Although it improves IAQ by reducing CO₂ accumulation, it can negatively impact TC and increase the heating energy demand (Zapata-Lancaster et al., 2023). Diaz (2021) identified a correlation between higher temperatures and elevated CO₂ levels, partly due to occupants keeping the windows closed in cooler weather to retain warmth. This behaviour highlights the significant role of occupant decisions in determining classroom CO₂ concentrations and overall IEQ (Diaz et al., 2021).

Zhang (2016) emphasised the challenges teachers face in regulating classroom ventilation due to inadequate window design or obstructive furniture, suggesting that larger, more accessible windows could improve teachers' ability to manage various IEQ parameters (Y. Zhang et al., 2016). Ma (2020) explored the implications of window usage on classroom ambience in colder climates, noting that while it can reduce CO₂, it can compromise student comfort and increase heating costs (Ma et al., 2020).

Gaihre (2014) found that encouraging teachers to open windows helps dilute CO₂ concentrations but often fails to maintain levels below the 1000 ppm benchmark, indicating that window ventilation alone may be insufficient for adequate air exchange (Gaihre et al., 2014). These findings collectively highlight the need for a balanced approach to classroom ventilation considering air quality and TC, potentially incorporating more sophisticated ventilation strategies beyond the dependence on window openings alone.

2.10.2 Summary of window opening behaviour

Window opening behaviour in primary school classrooms significantly affects IEQ, affecting factors such as TC, CO₂ levels, and energy consumption, with studies highlighting the complex interaction between ventilation, temperature regulation, and occupant comfort in educational settings.

2.11 Cognition and IEQ

The relationship between cognitive abilities, academic achievement, and environmental factors is complex and multifaceted. Traditionally viewed as unidirectional, recent research challenges this perspective with the theory of mutualism, proposing a bidirectional relationship between cognitive abilities and academic achievement (van der Maas et al., 2006). This theory suggests that skills connect through mutually beneficial interactions, strengthening relationships between cognitive abilities and academic performance.

Cognitive development in children progresses through stages, as described by Piaget's theory, from sensorimotor to formal operational thinking. Terman (1924) emphasised the importance of intelligence in academic achievement, while Nesayan et al. (2019) defined academic performance as educational evaluations issued in schools.

Environmental factors, particularly air quality, play a significant role in cognitive development and academic achievement. Air pollutants can negatively impact children's cognitive abilities through neuroinflammation, oxidative stress, and structural brain changes (B. Du et al., 2020; Nesayan et al., 2019; Taylor et al., 2016).

The school environment, as a crucial microsystem in the development of a child (Bronfenbrenner, 1979), interacts with other systems to influence cognitive growth. Poor IEQ in classrooms, including inadequate ventilation and high CO₂ levels, has been associated with a decrease in cognitive performance.

Research has linked specific cognitive functions, such as working memory and executive functions, to academic performance on various subjects. Processing speed, as defined by OIAP (Wickstrom, 2012), is central to many cognitive functions and

everyday activities.

Studies have investigated the relationship between student performance, IAQ, and classroom TC (Bakó-Biró et al., 2012; Fisk, 2000; Mendell and Heath, 2005; Wargocki and Wyon, 2007a). However, there is limited evidence on the association between classroom microclimate (TC&V) and cognitive functioning in primary school children, which presents a gap in understanding the link between IEQ and cognitive performance.

This research investigates the relationship between TC&V in classrooms and their impact on cognitive performance, including concentration, reasoning, and short-term memory. Understanding these interactions is crucial for developing effective educational strategies and creating optimal learning environments that foster cognitive growth and academic achievement.

Cognitive studies

Current evidence on the association between IAQ, TC, and cognitive performance of school children is limited, but suggests that CO₂ levels and temperature can significantly impact human cognition and decision-making.

Studies have shown that

- Increased CO₂ levels (>2000 ppm) can lead to a 5% decrease in attention (Coley et al., 2007).
- Improved ventilation rates (5.2 to 9.6 L/s.p) can enhance cognitive performance speed (Bakó-Biró et al., 2012; Wargocki and Wyon, 2007b).
- Higher CO₂ concentrations (1000-2500 ppm) can result in substantial decreases in decision-making metrics (J. Allen et al., 2017; Satish et al., 2017).
- Children may be more sensitive to higher temperatures than adults, preferring cooler conditions (Teli et al., 2012).
- Lowering classroom temperatures by 1 °C (in the 20-25 °C range) can improve performance speed by approximately 4% (Wargocki and Wyon, 2017b).

- A 1 °C increase in the annual average temperature correlates with a 0.02 standard deviation decrease in mathematics performance (Goodman et al., 2018).

To optimise learning environments, research suggests:

1. Maintaining CO₂ levels below 1000 ppm (Chatzidiakou et al., 2015).
2. Increasing ventilation rates up to 9 L/s.p (Wargocki and Wyon, 2007a, 2007b).
3. Keeping classroom temperatures between 20 °C and 22 °C (World Health Organization et al., 1987).

These measures can improve cognitive function, reduce absenteeism, and enhance overall academic performance. However, more research is needed to establish definitive guidelines for optimal IAQ and thermal conditions in educational settings.

Optimising test scheduling based on fluctuations in cognitive performance

The study conducted by Jarraya, Jarraya, and Souissi (2014) reveals that the cognitive performance of a typical classroom starts at lower levels, increases in the middle to late morning, experiences a decline after lunch (known as the post-lunch dip) and then increases again during the middle of the afternoon.

Maintaining proper TC&V levels in classrooms is crucial to maximise student cognitive performance and general comfort, ultimately leading to better academic results.

2.11.1 Summary of cognition and IEQ

The complex relationship between cognitive abilities, academic achievement, and environmental factors is a subject of ongoing research. Recent studies challenge the traditional unidirectional view, proposing a bidirectional relationship through the theory of mutualism. This perspective suggests that skills strengthen each other through mutually beneficial interactions, enhancing the connection between cognitive abilities and academic performance. Environmental factors, particularly air quality and TC, are crucial in cognitive development and academic achievement. Poor IEQ in classrooms, including inadequate ventilation and high CO₂ levels,

has been associated with a decrease in cognitive performance. Research has linked specific cognitive functions, such as working memory and executive functions, to academic performance on various subjects. However, there is limited evidence on the association between classroom microclimate (TV&V) and cognitive functioning in primary school children, which presents a gap in understanding the link between IEQ and cognitive performance. This research aims to investigate this relationship, focussing on concentration, reasoning, and short-term memory, to develop effective educational strategies and create optimal learning environments that foster cognitive growth and academic achievement.

2.12 Measurement and monitoring techniques

Measurement of IEQ is essential to maintain healthy, comfortable and productive indoor environments (Mamani et al., 2022; Voigt and Pelikan, 2010). Various techniques and instruments assess the levels of pollutants and environmental parameters that contribute to IEQ. These strategies include direct detection of chemical and biological contaminants, monitoring physical factors such as temperature, RH, and airflow, and evaluating perceptions of the occupants and health symptoms related to air quality. Given the complexities of indoor environments and the myriad substances affecting air quality, such as VOCs, PM, CO₂, and microbial organisms, IEQ measurement is inherently multidisciplinary, involving chemistry, physics, biology, and engineering principles. An accurate and reliable IEQ assessment is essential for the health of the occupants and informs the design, maintenance, and operation of the HVAC system in the building to create sustainable indoor spaces that promote health.

Aim 1 of the research focusses on CO₂, temperature, and RH measurement techniques, as these parameters are pivotal in determining TC&V levels. CO₂, a by-product of human respiration, indicates adequate ventilation in indoor spaces. Temperature and RH are critical physical parameters that affect thermal comfort and influence the concentration and survival of airborne pollutants, including pathogens. Cognitive functioning related to concentration, reasoning, and short-term memory will also be measured.

2.12.1 Monitoring CO₂

Monitoring metabolically generated CO₂, which refers to CO₂ exhaled by humans in indoor environments, is crucial for estimating ventilation rates, ensuring good TC&V, and assessing the risk of airborne disease transmission. The primary technologies used to monitor CO₂ concentrations are:

- **Non-dispersive infrared (NDIR) sensors:** These operate by directing infrared light through a gas sample and measuring the light absorbed by CO₂, correlating this to CO₂ concentration levels (Dinh et al., 2016).
- **Chemical sensors:** These detect CO₂ through colour changes or electrical property alterations due to a reaction with CO₂ (Santonico et al., 2020).
- **Photoacoustic spectroscopy sensors:** Using the photoacoustic effect, CO₂ molecules absorb light, heat up, expand, and generate detectable acoustic signals (Santonico et al., 2020).
- **Metal oxide semiconductor (MOS) sensors:** These detect CO₂ through changes in electrical resistance when the gas interacts with a metal oxide surface. However, they are less selective than the NDIR sensors (Santonico et al., 2020).
- **Tunable diode laser (TDL) sensors:** Using a diode laser, these sensors measure the gas concentration based on absorption at specific wavelengths, offering high accuracy and selectivity but at a higher complexity and cost (Somesfalean, 2004).

The choice of CO₂ sensor depends on factors such as accuracy, cost, maintenance, and monitoring type. NDIR sensors are widely popular for their balance of accuracy, stability, ease of use, and cost-effectiveness, making them popular in building HVAC systems, portable air quality metres, and smart home devices. **This research uses NDIR sensors.**

2.12.2 Monitoring temperature and relative humidity

Various methods and devices are available for monitoring temperature and RH in indoor environments, each with different levels of accuracy, cost, and complexity. These include:

- **Thermometers:** Traditional mercury or alcohol thermometers can be used to measure dry bulb temperature, but digital thermometers are preferred for their speed and accuracy in IEQ evaluations (Santonico et al., 2020).
- **Thermo-hygrometers:** These instruments measure both temperature and RH, offering a convenient solution to monitor these important IEQ parameters simultaneously in residential and commercial settings (Marques et al., 2018).
- **Infrared thermometers/thermal imagers:** Infrared thermometers and thermal imagers can measure surface temperatures from a distance by detecting infrared radiation, providing broader area coverage and visualising temperature distributions (Marques et al., 2018).
- **Psychrometers:** Psychrometers use two thermometers, one dry and one covered with a moist cloth, to measure dry-bulb and wet-bulb temperatures. The difference between these readings allows for the calculation of the RH (Santonico et al., 2020).

The choice of monitoring method will depend on the specific requirements of the environment, the desired precision, cost considerations, and the intended use of the collected data.

2.12.3 Advances in sensor and data logging technologies for real-time monitoring

Sensor technologies for real-time CO₂, temperature, and RH monitoring have undergone substantial advances, significantly improving IEQ management. These developments have resulted in more precise, reliable, and networked monitoring tools, which have several key features:

1. **Miniaturisation:** Modern sensors are smaller and more discreet, easily integrated into portable devices, wearables, and a wider range of Internet of Things (IoT) applications, minimising visual and physical impact (Boulic et al., 2024).
2. **Wireless connectivity:** Adopting Wi-Fi, Bluetooth, Zigbee, and other protocols facilitates seamless data transmission to central monitoring systems or cloud platforms, enabling remote surveillance and automated control (Y. Wang et al., 2017).

These enhancements are essential to promote healthier, more comfortable, and efficient indoor spaces, allowing swift and effective responses to indoor environmental changes based on accurate real-time data.

2.12.4 Challenges in TC&V monitoring

Implementing sensor technology for monitoring TC&V in schools poses different challenges due to the nature of high-traffic environments and the curiosity of young students. The risks of equipment damage, loss, and malfunction require a range of preventive measures:

- **Durability:** Devices must be durable, resistant to regular wear and possible rough handling. Protective casings may be necessary to protect them from impacts and rough treatment (Somesfalean, 2004).
- **Secure installation:** Installation in secure, tamper-proof locations is crucial to preventing intentional or accidental damage. Sensors should be out of direct reach to minimise the risk of being tampered with or knocked over (D. Zhang et al., 2022).
- **Vandalism prevention:** The potential for vandalism requires vandal-resistant designs or strategic placement in areas where supervision can deter tampering (Ministry for the Environment, 2009).
- **Routine maintenance:** Regular checks and maintenance are required to ensure proper functioning. A damaged equipment reporting system can facilitate quick responses (Ministry for the Environment, 2009).
- **Education:** Educating students about the importance of monitoring equipment and its role in maintaining a healthy learning environment can foster respect and proper treatment of the devices (Marques et al., 2018).
- **Asset management:** Tracking systems can help manage portable equipment, allowing easier recovery of misplaced items and monitoring the movement of equipment (Ministry for the Environment, 2009).
- **Cost management:** Adopting cost-effective monitoring solutions and accounting for replacement and repair within the school budget can accommodate the increased risk of equipment damage or loss (Ministry for the Environment, 2009).

- **Backups:** Having spare devices can mitigate downtime and replacement costs due to damage.

2.12.5 Measurement of cognitive tests

The equipment for tracking and recording the TC&V information has been outlined in **Section 4.3.3**; thus, this section will not be reiterated.

The administration of cognitive assessments was facilitated through an online testing interface provided by Creyos. An elaboration on the recording method, the specifics of the platform, and the rationale behind the use of the Creyos system for these purposes will be further explored in **Section 2.12.5**.

Assessment of cognitive performance has been used for more than 170 years. It was first reported in the case of Phineas Gage, who had an iron rod through his head (Teles Filho, 2020) and survived, although with a modified personality. Cognitive assessment became standard in the late 1950s and is often based on subsets of cognitive processes (Sternin et al., 2019).

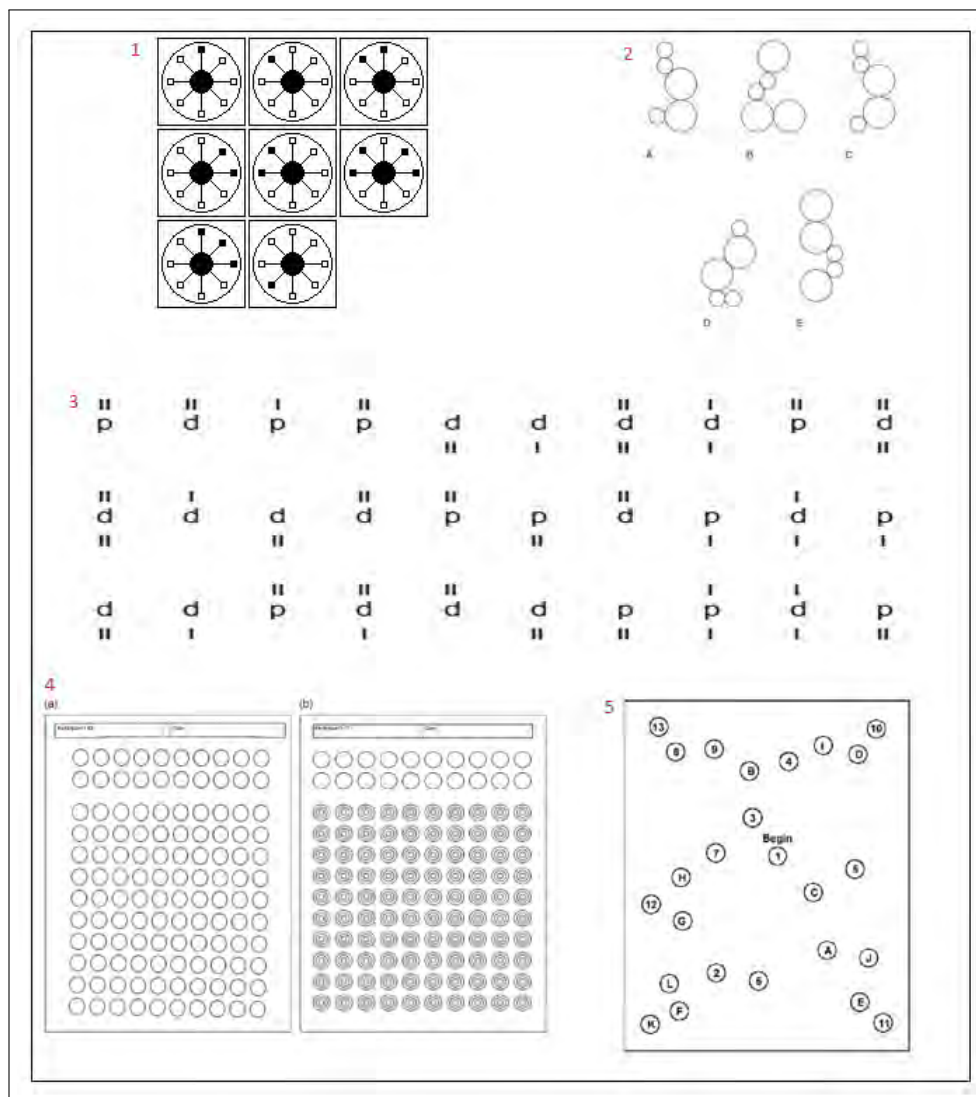
Cognitive performance tests require the participant to answer, at their best, a series of questions or solve problems, which usually have the correct answers (Sternin et al., 2019). If the test is paper-based, the instructions provided by the person administering the test need to be clear and consistent. The test administrator must be well trained in the administration protocols of those tests and possess the interpersonal skills necessary to build rapport with the students (Sternin et al., 2019). The administrator also needs to have the ability to deal with any issues that might occur during the test to ensure the validity and reliability of the research. After that, the results must be interpreted following standardised methods (Sternin et al., 2019).

With the advent of computers in the 1980s, existing 'pencil-and-paper' cognitive tasks were digitised. Using computers soon led to the creation of tests that assessed students' abilities more efficiently than pencil-and-paper equivalents. The responses could be measured with millisecond accuracy and recorded (Sternin et al., 2019). The computers could process the results instantly and, if required, adjust the difficulty of the test (Sternin et al., 2019). Automation of instruction and feedback, practice questions, and administration of large sample groups became easier (Sternin et al.,

2019). With the growing database, scoring reports became faster, easier, and more accurate.

Figure 2.10 provides five examples of cognitive tests based on pencil and paper. Tests 1 and 2 are associated with abstract reasoning, in which the participant has to identify which image does not belong.

FIGURE 2.10: *Examples of Various Paper-based Cognitive Tests*



Source: adapted from Institute of Medicine, 2015

Test 3 measures processing speed and rule compliance. Depending on the instruction, the participant in one round must count the d with | above it. The participant must

count p in the next round with l below it.

Tests 4 (a) and (b) are progressive. This is a serial dotting test, or for more advanced students, the prick test. The circle is more generous in (a), whereas in (b), the circle is much smaller. The aim is to be as accurate as possible and place your mark or hole in the middle of the circle.

The final test, number 5, is the number connection test. The student must connect all the dots without lifting their pen or going back over any lines.

Creyos Platform

Creyos, formerly known as Cambridge Brain Sciences (CBS), offers a comprehensive web-enabled platform for cognitive assessments suitable for a diverse demographic, including children, adolescents, and adults. This platform enables users to self-administer 12 distinctive tasks derived from well-validated neuropsychological tests, modified for remote use as highlighted by Hampshire, Highfield, Parkin and Owen (2012).

Each task dynamically adjusts complexity according to the user's performance, as Thienel, Borne, et al. (Thienel et al., 2023) described. Through adaptive testing mechanisms, the system maintains an optimal challenge level, thereby avoiding the "floor and ceiling" effects that could obscure the true abilities of test-takers. However, this adaptivity necessitates a broad difficulty range and a finely tuned algorithm to ensure accuracy, especially for those with exceptionally high or low performance levels. To maintain the precision and relevance of the assessment results, Creyos uses 'validity' measures as detailed by Nichols, Wild, Owen, and Soddu (Nichols et al., 2021). These measures detect and flag abnormal results that could indicate discrepancies in the testing process.

Creyos offers 12 tests subdivided into four core cognitive domains: memory, reasoning, verbal ability, and concentration. The platform can be self-administered without a neuropsychologist or other trained personnel, offering more convenience than paper-based methods.

The tests are based on well-validated neuropsychological tasks and have been adapted for Internet and computer-based testing (Sternin et al., 2019). The platform has accumulated approximately 4.5 million test results from around 400,000 participants, with about 75,000 scores contributing to research linking cognitive tasks and IQ scores (Hampshire et al., 2012). Creyos tests have been rigorously validated in numerous studies involving healthy populations and individuals with medical conditions (Nichols et al., 2020; Nichols et al., 2021; Wild et al., 2018). Previous research has also used these tests to explore the cognitive effects of indoor thermal conditions (Barbic et al., 2022; W. Luo et al., 2023)

The Creyos platform includes a statistically meaningful change index, which uses test-retest reliability and the standard deviation of scores (measured in the control sample) of each task to describe the range of possible differences that could occur with repeated completion of tasks (Sternin et al., 2019). If the change in performance of a participant from one point to another is significantly greater than expected, it indicates a meaningful change. For research requiring participants to repeat the same battery of tests, there is a risk of learning effects that skew the results. However, this is not an issue with the Creyos platform. The tasks are designed to be novel each time (Sternin et al., 2019).

Developed based on well-established psychological principles, these tasks have been validated for their high test-retest reliability, ensuring that users can trust the consistency of their performance measured over time. Readers looking for a detailed explanation of these tasks and their theoretical underpinnings can refer to the seminal work of Hampshire, Highfield, Parkin and Owen (2012).

1. Assessment tasks have been validated by more than 25 years of research by individuals around the world. **Table 2.14** outlines the details of several recent studies, all of which used the Creyos platform. The size of the study ranged from 20 to 86, with studies conducted in Italy, Canada, the United States, NZ, and Australia.
2. The settings in which the tests are administered realistically simulate the typical conditions encountered in a learning environment to ensure that the findings apply to real world situations.

TABLE 2.14: *Sample of Studies Validating the Use of Creyos Test Platform*

Reference	Research	Participants	Institution
Barbic et al., 2022	Effects of a cool classroom microclimate on cardiac autonomic control and cognitive performances in undergraduate students	20 university students	Department of Internal Medicine, Humanitas Clinical and Research Center, IRCCs, Rozzano, Italy
Honarmand et al., 2019	Feasibility of a web-based neurocognitive battery for assessing cognitive function in critical illness survivors	20 ICU patients	Department of Medicine, Western University, London, Ontario, Canada
Ko et al., 2020	The impact of a view from a window on thermal comfort, emotion, and cognitive performance	86 university students	Center for the Built Environment, University of California, Berkeley, USA
C. Wang et al., 2020	A randomised control trial and comparative analysis of multi-dimensional learning tools in anatomy	52 university students	Department of Anatomy, School of Biomedical Sciences, University of Otago, Dunedin, NZ
X. Zhang et al., 2017	The effects of higher temperature setpoints during summer on office workers' cognitive load and thermal comfort	26 office workers	The University of Sydney School of Architecture, Design and Planning

By adhering to these principles, the study aims to ensure that the variables reflect the theoretical constructs and provide a meaningful and applicable understanding of how environmental conditions affect cognitive functions in educational settings.

Duration of cognitive test

The determination of the duration of the task is based on research provided in Table 2.15.

TABLE 2.15: *Summary of Studies Related to Duration of Cognitive Tests*

Author	Sample size	Age of participants	Duration of cognitive test (min)
Bluyssen et al., 2020	335	Primary school children	45
Green et al., 2009	181	8-15	30-45
Haring et al., 2015	205	18-43	Depends on the number of tests incorporated each round.
Bik-Multanowski et al., 2011	49	>16	60-70
Sheppard and Cheatham, 2017	78	7-9	60-120
Syv��ja et al., 2014	224	12	45
Syv��ja et al., 2015	230	12	45
van der Niet et al., 2015	80	8-12	3

2.12.6 Summary section of measurement and monitoring techniques

This section provides an in-depth overview of the monitoring of IEQ parameters that are crucial to maintaining healthy and productive indoor environments. It outlines the importance of measuring CO₂, temperature, and RH in assessing TC&V efficacy. Various techniques and sensors, such as non-dispersive infrared sensors and thermohygrometers, are discussed for monitoring these parameters accurately. In addition, advancements in sensor technologies for real-time monitoring, including miniaturisation and wireless connectivity, are highlighted for efficient IEQ management. Challenges in monitoring TC&V in schools, such

as durability, secure installation, and prevention of vandalism, are also addressed. Furthermore, the section delves into cognitive performance testing using the Creyos platform, which offers 12 cognitive tasks validated through extensive research. The adaptivity, reliability, and usability of the platform in diverse demographic groups make it a valuable tool to evaluate cognitive functions. Finally, the section explores the duration of cognitive tests based on research findings, ensuring the tasks' relevance and applicability in educational settings. The detailed insights provided in this chapter lay the groundwork for assessing the impact of indoor environmental conditions on cognitive performance in primary school classrooms.

2.13 Summary of key findings

1. Thermal comfort and IAQ in NZ classrooms:

- Research shows that NZ primary school classrooms often experience suboptimal TC ($T < 18\text{ }^{\circ}\text{C}$ and $T > 24\text{ }^{\circ}\text{C}$) and ($RH < 40\%$ and $> 60\%$ range), and IAQ, especially with respect to elevated CO_2 levels ($> 800\text{ ppm}$) and poorly regulated temperatures.
- Classrooms often exceed the recommended CO_2 threshold of 1000 ppm, particularly during the colder months, when the windows remain closed to conserve heat.
- Historical and contemporary data indicate a prevalence of classrooms with temperatures that are either too low or too high, affecting student comfort and performance.

2. Impact on cognitive function:

- Elevated CO_2 levels ($> 1500\text{ ppm}$) are correlated with reduced cognitive functions, including concentration, short-term memory, and reasoning skills.
- Studies indicate that lower temperatures around $20\text{ }^{\circ}\text{C}$ to $22\text{ }^{\circ}\text{C}$ are optimal for cognitive functionality, improving task speed and accuracy.
- Poor IAQ negatively influences cognitive functioning and overall academic performance.

3. Behavioural and environmental influences:

- Teacher and student behaviours, such as window and door opening patterns, significantly impact ventilation and IEQ.
- External factors, such as seasonal variations and building designs, also affect the efficacy of these ventilation practices.
- Understanding these behaviours can lead to better management strategies to maintain optimal IEQ in classrooms.

4. Challenges in ventilation and insulation:

- Older school buildings, particularly those built before the 1990s, often lack adequate insulation, contributing to poor TC.
- Improved airtightness in newer buildings can reduce natural ventilation rates, which requires better ventilation solutions to maintain IAQ.
- When comparing the impacts of natural ventilation versus mechanical ventilation, the findings suggest that while mechanical systems generally provide better IAQ, natural ventilation can be effective if properly managed.

5. Policy and design recommendations:

- Current standards may not adequately address the unique climatic and structural conditions; thus, a reevaluation is necessary.
- Implementing scheduled "refresh breaks" for proper ventilation can significantly improve IAQ.
- Policies promote a balance of energy efficiency and adequate ventilation to ensure healthy and conducive learning environments.
- Future classroom designs integrate effective insulation and flexible ventilation systems to accommodate seasonal changes and ensure consistent IAQ.

By addressing these key findings, the study aims to optimise classroom environments in NZ, potentially informing better educational policies and practices that support students' health and cognitive performance.

2.14 Timeline of doctoral research

Embarking on a part-time doctoral study requires a carefully structured timeline to manage the unique balance between academic rigour and personal or professional commitments. The timeline provided in **Table 2.16** provides a comprehensive overview of a part-time doctoral study focused on the installation and analysis of IEMs; the administration of window surveys and the conduct of cognitive studies in various educational institutions throughout NZ.

From 2015 to 2024, the PI conducted a multi-phased research program encompassing foundational surveys, iterative IEM installations and field studies in diverse NZ locations (Auckland, Hawke's Bay, Christchurch, Dunedin, South Island). This involved observation protocols, cognitive testing within schools, and continuous review and data analysis of the literature. The program progressed from pilot studies to the deployment of advanced technologies, culminating in comprehensive data acquisition.

This chronological account serves as a detailed roadmap that highlights the PI's efforts to merge empirical research with innovative technology to enrich the academic fabric, thus contributing to a better understanding of built environments and their impacts on educational outcomes.

TABLE 2.16: *Timeline of Part-Time Doctoral Study (Mar '19 - Aug '24)*

Date	Location	Data Type	PI's Role	Data Collected	Aim	Sample Size
2015	AK	2 nd	n/a	Circulate Teachers window opening behaviour survey	Two	T=92
2017	AK	2 nd	RA	IEM pilot study	One	S=1, C=3
2017	HB, ChCh, Dund	2 nd	RA	Install and collect IEM data	One	HB S=2, C=4 ChCh S=4, C=12 Dund S=4, C=12
2018	ChCh, Dund	2 nd	RA	Retrieve IEM equipment from schools	One	ChCh S=4, C=12 Dund S=4, C=12
2018	ChCh, Dund	2 nd	RA	Circulate Teachers window opening behaviour survey	Two	T=35
Sept '19	AK			PI candidature approved		
End '19	AK			Two low risk ethics applications approved		
Feb '20 - Mar '23	AK			AK schools shut down - return of researchers to schools slow due to possible COVID-19 infections		
Early 2023	AK	1 st	PI	IEM pilot with new version.	One	S=1, C=3
Early 2023	AK	1 st	PI	Install IEMs in remaining classrooms	One	S=1, C=6
Mid 2023	AK	1 st	PI	Install 2 nd batch of IEMs	One	S=2, C=9
Mid 2023	AK	1 st	PI	Conduct window sensor pilot study	Two	S=1, C=3
Mid 2023	AK	1 st	PI	Install window sensors in remaining classrooms	Two	S=1, C=3
Mid 2023	AK	1 st	PI	Undertake window opening behaviour observations study	Two	S=1, C=6
Mid 2023	AK	1 st	PI	Conduct cognitive test pilot study	Three	S=1, C=3
2024	AK	1 st	PI	Log IEM data	One	S=1, C=6 S=2, C=9
2024	AK	1 st	PI	Log window sensor data	Two	S=1, C=6
2024	AK	1 st	PI	Conduct cognitive tests	Three	S=1, C=3
2024	AK	1 st	PI	Circulate Teachers window opening behaviour survey	Two	S=2, T=9

AK=Auckland, HB=Hawkes' Bay, ChCh=Christchurch, Dund=Dunedin
S=School, C=Classroom, T=Teacher

Chapter 3

FRAMEWORK

3.1 Introduction to research framework

This section serves as the foundation for research by first identifying the central problem under investigation and highlighting existing research gaps. The aims, questions, and objectives of the study are then described. After that, it delves into the theoretical background to contextualise the research questions and objectives within established theories and literature. Following this, a conceptual framework is crafted to identify the primary variables, concepts, and constructs that will be explored and to clarify their potential relationships. In addition, the section establishes the scope of the research by defining its boundaries and identifying areas outside of its main focus.

3.2 Research gap identification

- **Limited geographical focus:** Although several international studies have examined TC and IAQ in classrooms, a notable lack of research focused on NZ and its unique built environment and climate conditions. Limited literature addresses how these factors influence student well-being and cognitive performance in primary schools in NZ.
- **Lack of longitudinal data:** Existing studies have primarily relied on short-term or cross-sectional data, thus lacking a comprehensive understanding of seasonal variations and their long-term impact on student comfort and cognitive performance.
- **Insufficient focus on cognitive function:** Most of the research has focused on general health and comfort or academic results, with fewer studies investigating

how classroom environmental quality affects specific cognitive abilities such as concentration, short-term memory, and reasoning.

- **Behavioural aspects:** The influence of teacher and student behaviour on ventilation (e.g. window opening patterns) and its effect on IEQ have been under explored. This includes how these behaviours change under different weather conditions or seasons.
- **Inadequate data on classroom design and ventilation systems:** There is limited research on the effectiveness of different classroom designs and ventilation systems used in NZ schools, especially with regard to newer insulation standards and their effect on IEQ.
- **Impact of natural and mechanical ventilation:** The specific results of natural versus mechanical ventilation in maintaining optimal CO₂ levels, temperature, and RH of CO₂ in classrooms remain under examined, particularly in energy efficiency and cost.
- **Assessment of exposure:** Gauging schoolchildren's exposure to indoor air pollutants accurately is difficult due to the variation in day-to-day activities and the different environmental conditions between schools and within distinct areas of the same school.
- **Sensitive populations:** It is critical to identify and understand the impact of poor IEQ on vulnerable groups, such as children with asthma, allergies, or other health conditions, who could be more adversely affected by certain indoor pollutants than the general population.
- **Variability in educational settings:** The wide range of building designs, ventilation technologies, and maintenance practices, not to mention the array of school activities, make it a challenge to extrapolate the study findings to all educational settings. Each school may present a unique environment that impacts IEQ differently.
- **Complexity of indoor environments:** The indoor air environment is influenced by various factors, including building materials, occupant activities, ventilation rates, and outdoor air quality. This complexity makes it difficult to isolate the effects of specific pollutants on health.

- **Identifying vulnerable populations:** Different individuals may respond differently to the same pollution level due to age, pre-existing health conditions, and genetics. Identifying and protecting these vulnerable groups remains a challenge.

The identified research gaps underscore the need for a study that integrates NZ-specific environmental data with detailed analyses of how IEQ parameters affect cognitive performance in primary schools. By addressing these gaps, the current study aims to contribute valuable insight and practical solutions to optimise classroom environments to support student cognitive functioning and overall academic success.

3.3 Rationalisation for the necessity of the current study

1. **Relevance to NZ's educational context:** This study addresses NZ's distinct climate and building designs, which are important for tailoring effective educational policies that enhance IEQ in primary school classrooms.
2. **Holistic understanding through longitudinal analysis:** Conducting a longitudinal study across different seasons provides a comprehensive understanding of how seasonal variations in IEQ impact students, offering insights that short-term studies cannot.
3. **Targeting cognitive performance:** By focussing on specific cognitive functions such as concentration, short-term memory, and reasoning, the study aims to reveal how poor IEQ directly affects student learning outcomes.
4. **Behavioural insights:** Investigating factors that influence window and door opening patterns provides critical insight into classroom management strategies, leading to more effective IEQ practices.
5. **Evaluation of current standards:** Comparing study findings with existing standards helps evaluate their effectiveness, advocating for necessary updates to ensure optimal learning environments suited to NZ's unique requirements.
6. **Policy and design guidance:** The results of the study can inform policy-level guidelines and architectural practices, leading to better designed classrooms and improved IEQ management that improves student learning.

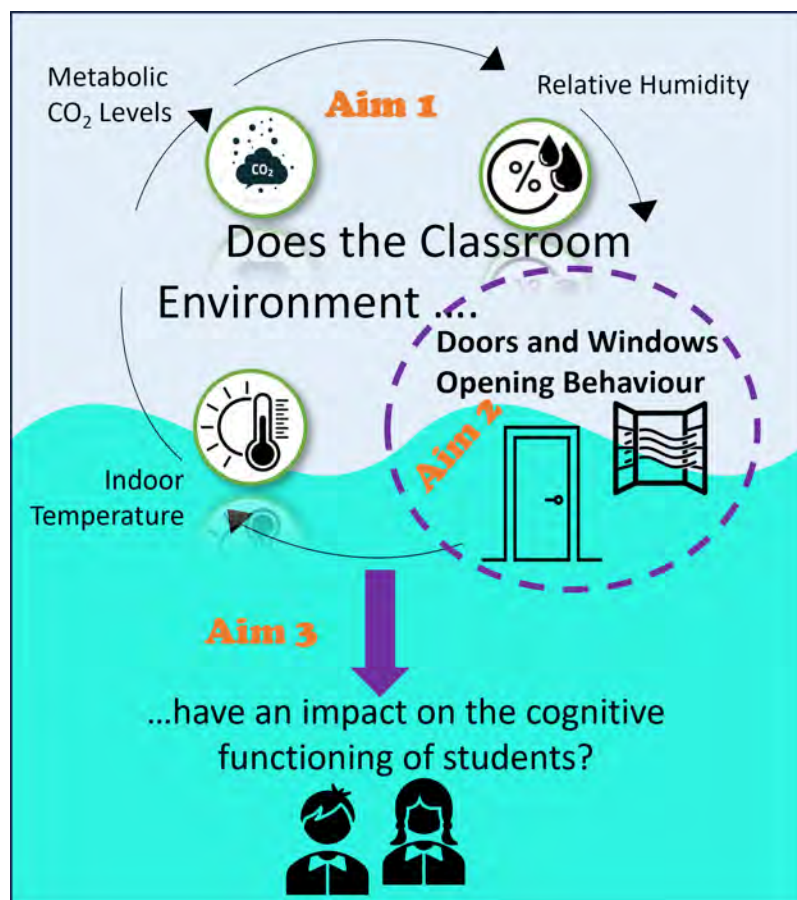
7. **Response to COVID-19:** Providing information on maintaining cognitively friendly environments during pandemic disruptions helps schools adapt to changing health conditions without compromising student performance.
8. **Evidence-based recommendations:** The findings offer evidence-based recommendations for policymakers and educational authorities to update standards and regulations for school environments.

By addressing these areas, the research seeks to provide actionable insights with real-world implications for various stakeholders and lay the foundation for ongoing research in the TC&V and cognitive functioning within educational environments.

3.4 Research aims

This study will focus on three objectives as detailed in the project conceptual framework in **Figure 3.1**.

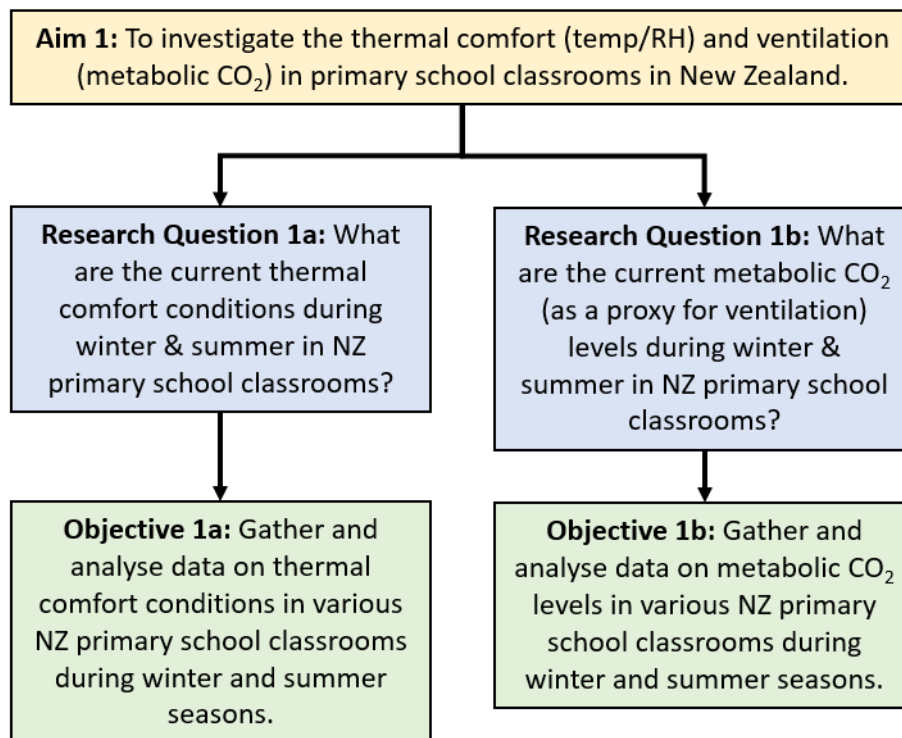
FIGURE 3.1: *Project conceptual framework*



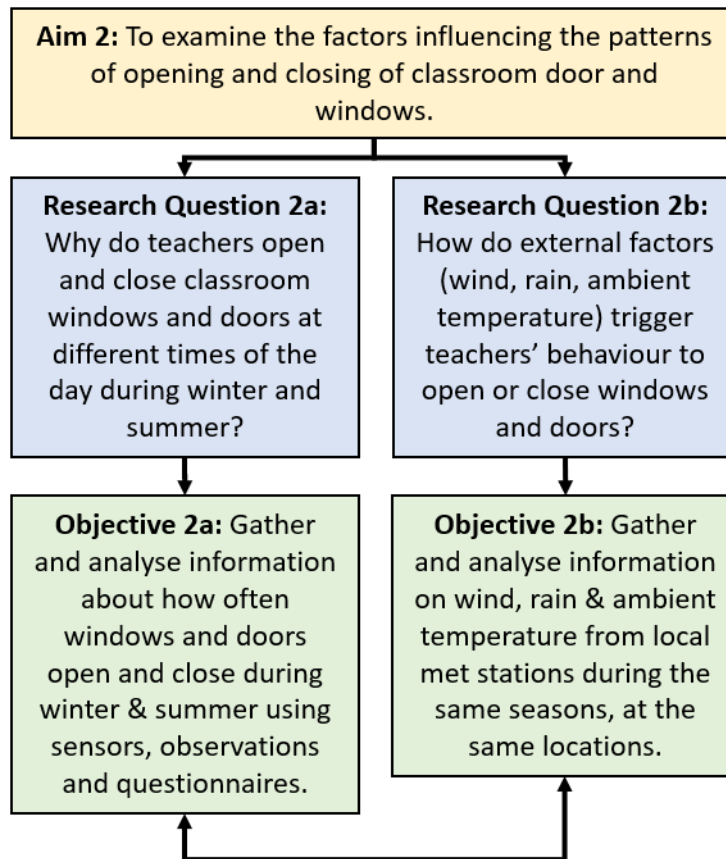
The three aims are:

- Aim 1, as outlined in **Figure 3.2**, investigates the thermal comfort (temperature and RH) and ventilation (metabolic CO₂ levels) of primary school classrooms in NZ.

FIGURE 3.2: *Outline of Aim 1*



- Aim 2, as outlined in **Figure 3.3**, examines the factors influencing classroom window and door opening and closing patterns.

FIGURE 3.3: *Outline of Aim 2*

Teacher window opening behaviour is crucial to understanding IAQ and its impact on cognitive function because it represents a significant point of **human intervention**. By controlling window opening, teachers directly influence ventilation rates (airing) and therefore levels of CO₂, volatile organic compounds, or VOCs, and other pollutants known to affect cognitive performance. This makes their behaviour a key variable to consider, providing a more nuanced and realistic overview of the dynamics of classroom air quality.

As can be seen from this doctoral study, in 2015 only 40% of Auckland teachers opened their windows while they taught. This percentage dropped to 15% in Christchurch, Dunedin, and Hawke's Bay (Boulic et al., 2019; Gully, 2015; Liang et al., 2012). These results are pre-COVID. However, when Auckland

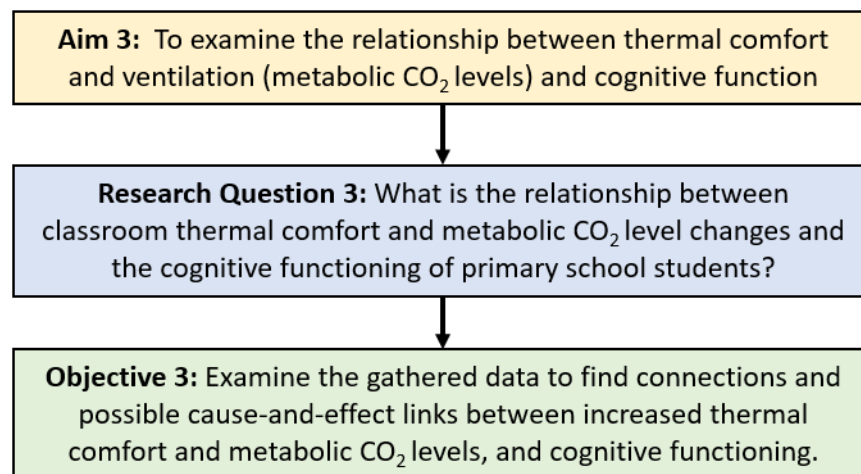
teachers were asked the same questions by the PI after COVID in 2024, the results were a surprising 30%.

While we might measure air quality parameters directly, understanding teacher behaviour gives us insight into **why** those parameters are what they are. It allows us to move beyond correlation and explore potential causal links.

Furthermore, it provides a practically relevant point of intervention. If we can identify specific teacher practices around window opening, we can develop targeted interventions and training programmes to improve learning environments. In essence, including teacher window opening behaviour adds a crucial layer of understanding to the complex relationship between IAQ and cognitive function in classrooms, bridging the gap between measurement and actionable strategies.

- Aim 3, as outlined in **Figure 3.4**, examines the relationship between thermal comfort and CO₂ levels and their impact on student cognitive function.

FIGURE 3.4: *Outline of Aim 3*



The selection of a mixed methods approach is based on the research questions posed, the depth of which cannot be explored only by quantitative or qualitative means (Creswell et al., 2009).

The research questions can be summarised as follows.

1. IEQ conditions in classrooms:

- Research Question 1a: What are the winter and summer thermal comfort conditions in primary school classrooms in NZ?
- Research Question 1b: What are the current metabolic CO₂ levels (as a proxy for ventilation) during winter and summer in NZ primary school classrooms?
 - Research Questions 1a and 1b require a quantitative approach to establish measurable baselines of thermal comfort and CO₂ levels, crucial to revealing tangible environmental conditions in classrooms during the different seasons in NZ.

2. Teachers' ventilation practices:

- Research Question 2a: Why do teachers open and close classroom windows and doors at different times of the day during winter and summer?
- Research Question 2b: How do external factors (wind, rain, ambient temperature) impact teachers' behaviour to open or close windows and doors?
 - Research questions 2a and 2b call for a qualitative exploration to comprehend the depth behind teachers' motivations and behaviours in ventilating classrooms, further complemented by quantitative observations to outline how external environmental factors mould these behaviours.

3. IEQ and cognitive functioning:

- Research Question 3: What is the relationship between classroom thermal comfort and metabolic CO₂ level changes and the cognitive functioning of primary school students?
 - Research question 3 requires a sophisticated blend of quantitative and qualitative methodologies to elucidate the relationship between IEQ conditions and cognitive performance, ensuring that the research embraces the complexity and multidimensionality of the subject matter.

The study employs a mixed methods approach to provide comprehensive environmental measurements and explore behaviours and cognitive outcomes. This approach combines quantitative data, providing objective clarity and generalisability, with qualitative inquiry, capturing contextualised human experiences (Guba, Lincoln, et al., 1994). This combination enhances understanding, allowing numerical precision to intersect with interpretive insights, thus enriching the research findings.

Integrating diverse data types leads to a more profound, triangulated understanding of how student experiences influence educational spaces. By aligning the methodological approach with the research questions, this study justifies the selection of mixed methods as a strategy that takes advantage of each strengths.

3.5 Analysis of the research problem

The general objective of the PI is to investigate the impact of TC and metabolic CO₂ on the cognitive function of primary school students using an online cognitive tool.

To address these challenges, it is imperative to understand diverse forms of exploration and to use tools to investigate and visualise the relationship between TC, metabolic CO₂ and cognitive function. These efforts aim to improve our understanding of these factors and contribute to better educational environments. This will be done by:

- Exploring the TC and metabolic CO₂ levels associated with primary school classrooms.
- Investigating the behaviour of teachers to understand why they open and close windows and doors.
- Discover the relationship between TC and metabolic CO₂ levels and cognitive function.

There are several features of this problem.

1. Generalisability (scope)
2. Sampling strategy
3. 'Why' or 'What'
4. Interdisciplinary aspects
5. Time horizon

3.5.1 Generalisability (scope)

The challenge of comprehending and assessing the levels of thermal comfort and CO₂ in primary schools and their influence on cognitive function is context-specific and potentially applicable in broader settings. **Table 2.12**, a summary of NZ studies detailed in Chapter 2, highlights research on thermal comfort (temperature and relative humidity) and CO₂ levels in the cities of Wellington, Christchurch, Invercargill and Taupo. In particular, the issue remains specific to NZ's largest city, Auckland, as no investigations have been carried out.

The topic of cognitive function in primary school children remains unexplored in existing publications. Consequently, the investigation into this aspect of the research has the potential to be specific or applicable to a broader context within NZ.

Generalisable research allows aims to be applied to a broader population or context. It also provides external validity, allowing the findings to be applied to situations beyond the specific conditions of the study, increasing the relevance of the research to a wider audience (Carminati, 2018; Rolfe, 2006; Weise et al., 2020). Researchers can also develop theories with broader explanatory power by examining patterns and relationships in diverse settings or populations (Carminati, 2018; Weise et al., 2020).

Furthermore, generalisable research allows for comparisons across different groups or settings. This can lead to a better understanding of variations and similarities, providing insight into the factors that influence the results (Carminati, 2018; Weise et al., 2020).

Generalisable research also contributes to the cumulative nature of scientific knowledge. Building on and integrating findings from various studies, researchers can develop a more comprehensive understanding of a particular phenomenon (Carminati, 2018; Weise et al., 2020). Generalisable research often involves more extensive and diverse samples, which can improve the statistical power of the study. This, in turn, increases the reliability and generalisability of the findings (Carminati, 2018; Weise et al., 2020).

It is evident from **Table 3.1** that all the publications presented are specific in their research nature. Only two publications had sample sizes that warranted their findings being generalisable to the research region and other areas of NZ Climate Zone 3.

TABLE 3.1: *Summary of NZ IEQ Publications Generalisability Status*

	Specific or General											
	Research Question		Objectives		Methodology		Sample Size		Applicability of Findings		Literature Review	
	S	G	S	G	S	G	S	G	S	G	S	G
Bassett, 1999												
Cutler-Welsh, 2006												
McIntosh, 2011												
Trompetter, 2018												
Bennett, 2019												
Ackley, 2022												
NIWA, 2022												

3.5.2 Power analysis and sampling strategy

The PI, navigating the complexities of research during the COVID-19 pandemic, encountered significant constraints when conducting a power analysis for the study in primary schools. The unpredictable and necessary public health measures, including intermittent school closures and Massey University's stringent travel restrictions outside Auckland, directly impacted the ability to collect data across a

broad geographic region as originally intended.

Recognising the limitations placed on the scope and scale of the investigation, the PI recognised that the conventional approach to power analysis, estimating the sample size needed to detect a given effect with high confidence (H. Du et al., 2023) - was no longer feasible. The restrictions limited access to a diverse sample of primary school environments, limiting the ability to perform a robust power analysis based on larger sample sizes (H. Du et al., 2023).

Despite these challenges, the PI's commitment to methodological integrity led to exploring alternative strategies. The power analysis required reevaluation and recalibration based on the smaller, more localised sample available. This reassessment considered the revised expectations and potential limitations of statistical power resulting from a reduced sample size, while aiming to reach scientifically valid conclusions within the revised parameters.

Furthermore, the research required the exploration of alternative data collection methodologies, adapting techniques to fit the constraints while pursuing a meaningful inquiry into the research questions. This included a re-examination of statistical methods, potentially favouring those tailored for small sample sizes or those that could account for the increased variability expected in the data collected under these pandemic-induced conditions.

In conclusion, the need to adjust the power analysis in response to COVID-19 has reflected the current state of educational research amidst global challenges and highlighted the flexibility and innovation required of researchers to ensure the continuity and integrity of their work under unprecedented constraints.

Sampling strategy employed

The initial phase of the sampling strategy involved maintaining engagement with schools that had previously contributed to the IAQ research of Massey University. During a field visit from August to September 2019, covering schools in Christchurch and Dunedin, the PI articulated the research parameters of the current study. Following this presentation, most of these schools expressed a preliminary

agreement to participate in the research.

This sampling method is an example of purposive sampling, also known as judgemental or selective sampling. This approach is a type of non-probability sampling in which the researcher relies on their judgment to select the schools most advantageous to the research objectives (Berliner, 2002).

In the situation described by the PI, the PI chose to leverage existing relationships with schools that had previously engaged in similar research (Air Quality Indoor Studies at Massey University) (H. Du et al., 2023). These schools were selected because they are already somewhat familiar with the research context, which could make them more receptive to participating in further research and possibly having the required infrastructure or conditions relevant to the study. This method allows the PI to use their knowledge of the population to pick the subjects that will be the most informative for the research at hand (Berliner, 2002; H. Du et al., 2023).

The PI acknowledges that purposive sampling is efficient and provides a depth of understanding from a specific population subset. However, the findings may not be generalisable to all schools or contexts due to potential selection bias and lack of randomness in the sampling process (Berliner, 2002).

However, after the onset of COVID-19, participating schools in Christchurch and Dunedin could no longer contribute to the study. This change was due to the imposition of regional travel restrictions on PhD students, which necessitated refocusing the research scope. Consequently, the study was adjusted to include only schools in the Auckland region, as they were the most accessible under the new travel restrictions.

Based on this restriction, where the study's scope is limited to only Auckland schools due to COVID-19-related travel restrictions, the sampling strategy shifts to convenience sampling. Convenience sampling is a type of non-probability sampling where the sample is drawn from a part of the population that is close at hand or readily accessible to the PI (H. Du et al., 2023; Hess-Kosa, 2010).

However, in this case, the change was not driven by a strategic research decision but by external constraints that limited access to the initial intended population. As such,

schools that were accessible and available within the Auckland region constituted the convenient sample for the study.

The PI acknowledges that while convenience sampling is practicable and efficient, especially under restrictive conditions, it can limit the generalisability of study findings due to the potential for sampling bias and the fact that the sample may not adequately represent the larger population (H. Du et al., 2023).

Regrettably, the persistent closures of Auckland schools, which required students to transition to home schooling, led to a decision by the Boards of Trustees - comprised of parents - that they were not in favour of external researchers entering the schools. This position was taken to mitigate any additional risks of school closures and prioritise the health and safety of the school community during a period of increasing concern.

Consequently, an alternative sampling strategy was determined. The PI reached out to FRENZ (French-English New Zealand). This non-profit organisation supports the development and operation of quality bilingual French-English programmes in public schools in NZ. The rationale for this selection was associated with the research outputs of SINPHONIE (Schools Indoor Pollution and Health: Observatory Network in Europe). Of the five schools considered, three were located within the Auckland region, of which only two were primary educational facilities. However, one of these schools was under significant renovations and had already committed to collaborating with a different research team; consequently, they opted not to participate in the study. The remaining primary schools in the region agreed to participate in the research. The collaboration with this school began in early 2023.

Subsequently, a second primary school expressed a willingness to contribute to the study, although limited to Aim 1. The involvement in this school was initiated in November 2023.

The sampling strategies used in this study, given the changes and adaptations described, can be defined as follows.

1. **Purposive sampling:** Initially, schools that had previously been involved in related research were intentionally selected because they were likely to have the relevant characteristics for the study (Berliner, 2002).

2. **Convenience sampling:** Due to travel restrictions caused by COVID-19, the focus was shifting to Auckland schools due to their accessibility to PI (H. Du et al., 2023).
3. **Referral sampling:** After restrictions prohibited access to the initial set of schools, the PI leveraged their network by contacting FRENZ, a non-profit organisation, which served as an intermediary to identify potential schools that could participate in the study (Hess-Kosa, 2018).
4. **Selective sampling:** When presented with limitations, such as schools that undergo renovations or are willing to participate in only a portion of the study (Aim 1), the PI selectively engaged schools based on their availability and willingness to participate (H. Du et al., 2023).
5. **Sequential sampling:** This approach evolved with the need to continuously reassess and select new samples based on changing circumstances, permissions, and collaboration opportunities, starting from an initial stable sample and moving through various alternatives as conditions change (Berliner, 2002).

In summary, sampling strategies shifted from more purposeful and convenience approaches to a more reactive, opportunistic strategy, including referral and selective sampling, influenced by logistical constraints, institutional changes, and emerging opportunities. The overall plan was adaptive, responsive to obstacles, and took advantage of accessible opportunities, thus ensuring the continuation of the research despite challenging circumstances.

3.5.3 'Why' or 'What'

It is essential to provide a balanced qualitative and quantitative description of a problem, particularly when the subjects are people. This facilitates a more comprehensive and robust approach to problem analysis and decision making, ensuring that both the depth and the breadth of the problem are adequately addressed (Berliner, 2002; Guba, Lincoln, et al., 1994). This involves finding equilibrium in clarifying the 'why' behind a phenomenon and detailing 'what' occurs. Upon re-visiting the research questions and objectives of the study, it becomes evident that the initial focus should be on establishing 'what' is happening rather than delving into the 'why' at the outset. This points the research towards a methodological position that primarily incorporates quantitative analysis for 'Aim 1', since the main

variables of thermal comfort and CO₂ levels are numeric. However, 'Aim 2' and 'Aim 3' are a mix of 'what' happens and 'why' it happens.

3.5.4 Interdisciplinary aspects

This research draws on multiple disciplines. It draws on knowledge from environmental science and engineering, building science and architecture, occupational health and safety, neuroscience and psychology, biomedical engineering and neurophysiology, and data science and statistics. As such, this will significantly influence the research design. The research will integrate quantitative methods for assessing thermal comfort, CO₂ levels and cognitive function with quantitative methods such as questionnaires and qualitative observation studies to capture subjective experiences. This supports the need for a mixed-method approach.

3.5.5 Time horizon

Time plays a pivotal role in the execution and outcomes of this research, shaping both the process and the interpretation of its findings. Given the longitudinal nature of the study, which observes variables between seasonal variations and different time intervals, the research will be able to capture dynamic changes and trends that are vital for understanding IEQ and its impact. School schedules, seasonal events, and the academic calendar will influence data collection periods and participant availability (Berliner, 2002). Moreover, the temporal context, especially significant due to COVID-19 disruptions, adds a layer of complexity, requiring flexibility in data collection windows and resulting in adaptations to research timelines. Unexpected delays and shifting scenarios require a realistic assessment of time as a resource, taking into account extended data analysis phases, possible resampling, and a reassessment of the research design. The time factor also underscores the importance of maintaining rigorous project management and contingency planning to navigate these temporal challenges efficiently.

Summary of research problem

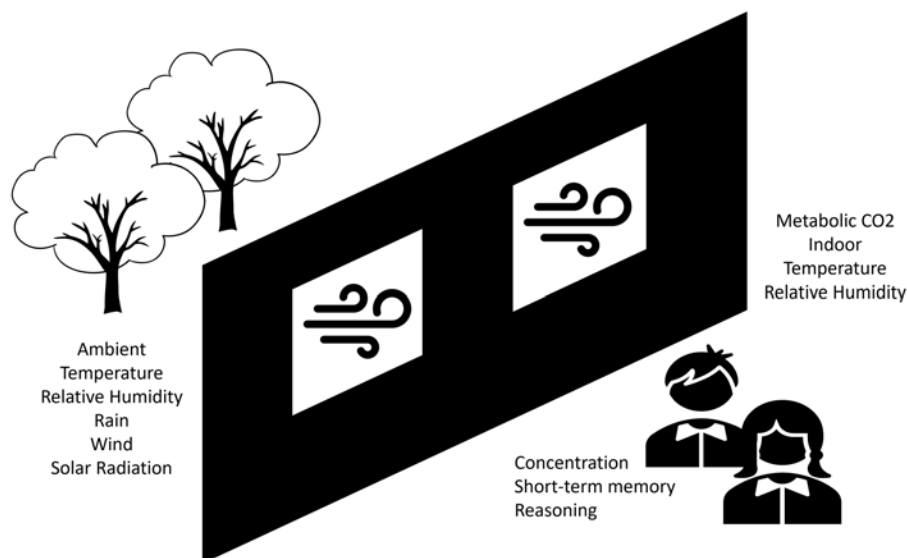
In summary, the problem can be described as specific, mixed methods, interdisciplinary, and longitudinal. Considering that the nature of a research problem determines its approach to resolution (J. Tookey, 1998), the methodological framework and research methods chosen should be in line with

these inherent characteristics. The next step is to establish the most appropriate philosophical position for the research before selecting the appropriate method(s).

3.5.6 Variables investigated and measured

To establish the boundaries of this research, **Figure 3.5** depicts the various factors that will be analysed. The study examines external variables such as ambient temperature, RH, rainfall, and wind speed. It also investigates internal classroom variables, including indoor temperature, RH, and CO₂ concentrations. Furthermore, the study will explore door and window opening patterns, as these behaviours significantly influence the TC&V of the classroom. The neurocognitive functions considered include concentration, short-term memory, and reasoning.

FIGURE 3.5: *Framework Variables*



Some variables that remain constant throughout are primary school classrooms, thermal comfort, and CO₂ used as a proxy for ventilation (TC&V).

- Primary school classrooms have been specially selected for this doctoral research. Primary students are generally taught in the same room all day, whereas secondary and university students usually occupy the space for a shorter period.
- The independent variables under investigation are measures of TC&V:

- The presence and control over these variables are engineering decisions which must satisfy a variety of requirements made by Building Regulations, Building Bulletins, Workplace Regulations, as well as users of the space. Therefore, they are relevant to PIs interested in the Built Environment.
 - They are some of the variables most commonly researched in environmental studies, but knowledge is limited in its application to the design and management of cognitive performance of educational buildings.
- Primary school classrooms have been specially selected for this research. Primary students are generally taught in the same room all day, whereas secondary and university students usually occupy the space for a shorter period.
 - The independent variables under investigation are measures of TC&V:
 - The presence and control over these variables are engineering decisions that must satisfy the requirements of Building Regulations, Building Bulletins, Workplace Regulations, and space users. Therefore, they are relevant to PIs interested in the Built Environment.
 - They are some of the variables most commonly researched in environmental studies, but knowledge is limited in its application to the design and management of cognitive performance of educational buildings.

3.6 Scope and limitations

3.6.1 COVID-19 limitations

The scope of this research, which spanned 5.5 years from March 2019 to August 2024, was affected by the unprecedented global crisis of the SARS-Coronavirus (COVID-19) pandemic. This unexpected occurrence deeply affected the methodology and participation, influencing the breadth and depth of the research results.

The project was initially conceived as a comprehensive investigation that would harness data from various educational settings to analyse the classrooms' TC&V

influence on cognitive functioning. However, the advent of COVID-19 and its disruptions made this impossible.

As the research began, schools already involved in Massey University's IAQ research, in Christchurch and Dunedin, affirmed their willingness to participate and support the study. Their formal agreements to participate were secured through discussions during field visits to each institution in August and September 2019.

Between February 2020 and March 2023, the pandemic was at its peak, forcing schools to shut down intermittently as part of public health measures to curb the spread of the virus. These closures, while necessary, significantly limited the capacity for on-site research. Moreover, Massey University's stringent Health and Safety protocols, particularly concerning travel outside Auckland, placed additional constraints on the movement of the PI and the ability to conduct fieldwork efficiently across the previously intended broad geographic region.

Following the pandemic, ongoing inter-regional travel restrictions limited the research exclusively to the Auckland region. However, a new set of challenges emerged. The tightened safety protocols in Auckland, which experienced some of the most stringent measures, led to the reluctance and withdrawals of most initially participating schools. The prevalent school closures cast a shadow of uncertainty and risk that the Boards of Trustees, comprising parents, were not inclined to exacerbate. They expressed concerns about the potential for increased exposure to COVID-19 resulting from the presence of external researchers, fearing additional closures and the burden of homeschooling that would follow.

Therefore, the scope of the study eventually evolved, bounded by the externalities imposed by a global health emergency. Although this reduced the range of participating schools and the data that could be collected, it also provided a unique lens through which to view TC&V's impact on cognitive functions during increased health awareness and environmental control. Despite the limitations, the circumstances allowed the research to forefront resilience and adaptability in educational research under crisis conditions, uncovering insights into management strategies and the flexibility of institutional learning environments.

As mentioned, undertaking this study as a part-time student presented a unique

set of challenges exacerbated by the unprecedented global COVID-19 pandemic. Of particular note was the impact of Auckland's sustained lockdowns and the implementation of the Traffic Light System, which signified a rolling landscape of regulations that directly impeded the PI's ability to access schools for research purposes.

A detailed breakdown of the various lockdowns that affect this doctoral study can be found in **Appendix D.1.2**.

Another limitation of the COVID-19 pandemic **was the restriction in the scope of neurocognitive tests that the PI could perform**. Initially, the research design included conducting electroencephalogram (EEG) recordings to examine Beta brainwave activities associated with stress and focus among students. This was to be examined while they participated in the Creyos online cognitive tests. Unfortunately, the Massey University Ethics Committee did not approve the high-risk ethics application necessary to include EEG measurements in the study due to increased health and safety concerns amid the pandemic. This restriction significantly altered the research methodology, precluding the acquisition of direct neurophysiological data, which would have enriched the understanding of cognitive states under varying TC&V conditions.

3.6.2 Observation study limitations

Conducting the observation studies in a school environment presented several limitations to the PI, a part-time doctoral student working as a Senior Tutor. The PI experienced these three main limitations while conducting the observation study.

- **Time constraints:** Balancing teaching responsibilities at Massey University with conducting the observation study could limit the time available for observations.
- **Observer effect:** The presence of an observer in the school environment can alter the natural behaviour of students and teachers. Participants may behave differently if they know that they are being observed, which can affect the validity of the data.
- **Physical and cognitive load:** Balancing the demands of teaching and conducting observational research can be physically and mentally demanding,

which affected the PI's ability to remain consistently attentive during observations. This was mitigated by immediately coding the observation forms upon returning to the school office on site. This allowed the PI to quickly revisit and double-check any events that may have been missed during that observation cycle.

3.6.3 Magnetic window sensor limitations

1. **Functional limitations of magnetic sensor:** An additional, albeit minor, limitation concerns the functionality of the magnetic sensors installed on the windows and doors. These sensors are designed to detect whether a window or door is open or closed (binary), but do not measure the extent of how wide they are open (degrees). Although a gyroscopic sensor could provide data on the degree of openness, such granularity was deemed unnecessary given the financial implications and the focus of the investigation, which does not include detailed ventilation studies. Consequently, the decision was made that the binary data provided by the magnetic sensors would be adequate for this research.
2. **Battery-operated sensors** have a limited lifespan due to their dependence on battery power. A low battery can reduce sensor functionality, potentially leading to data collection gaps. To address this, the batteries of all S1 sensors were changed twice during the study period.
3. Another limitation encountered was the **durability of the adhesive** used to mount the sensors. The adhesive was insufficiently robust, leading to some sensors falling off the windows. Although some teachers promptly informed the PI about these incidents, others did not, which resulted in gaps in data collection. This inconsistency in the reporting further contributed to disruptions in the continuity and completeness of the data set.
4. **The reliance on Bluetooth-enabled gateways** and USB drives for data collection and storage introduced delays or risks of data loss, especially during frequent circuit tripping in two classrooms. High-frequency tripping can disrupt the connectivity between sensors and gateways, resulting in incomplete data transfers and a possible loss of critical data points.

3.6.4 Cognitive study data analysis limitations

Aggregated data approach: The limitations of this study mean that such detailed personal data cannot be obtained and analysed. Instead, the research will aggregate data at the classroom level rather than dive into the nuances of individual student experiences. This approach naturally entails certain limitations regarding the personalisation of the data. However, it allows for a broad overview of the environmental conditions that affect the collective student body within the educational setting. Despite these constraints, the study aims to provide valuable insights into TC&V of classrooms and how these environmental factors could potentially influence the cognitive functioning of students in general.

In the context of this case study, students in years 5 and 6 **do not adhere to a uniform dress code**. This presents a limitation within the context of the study, as it precludes the possibility of taking standardised measurements of clothing insulation (clo) values for student participants.

Chapter 4

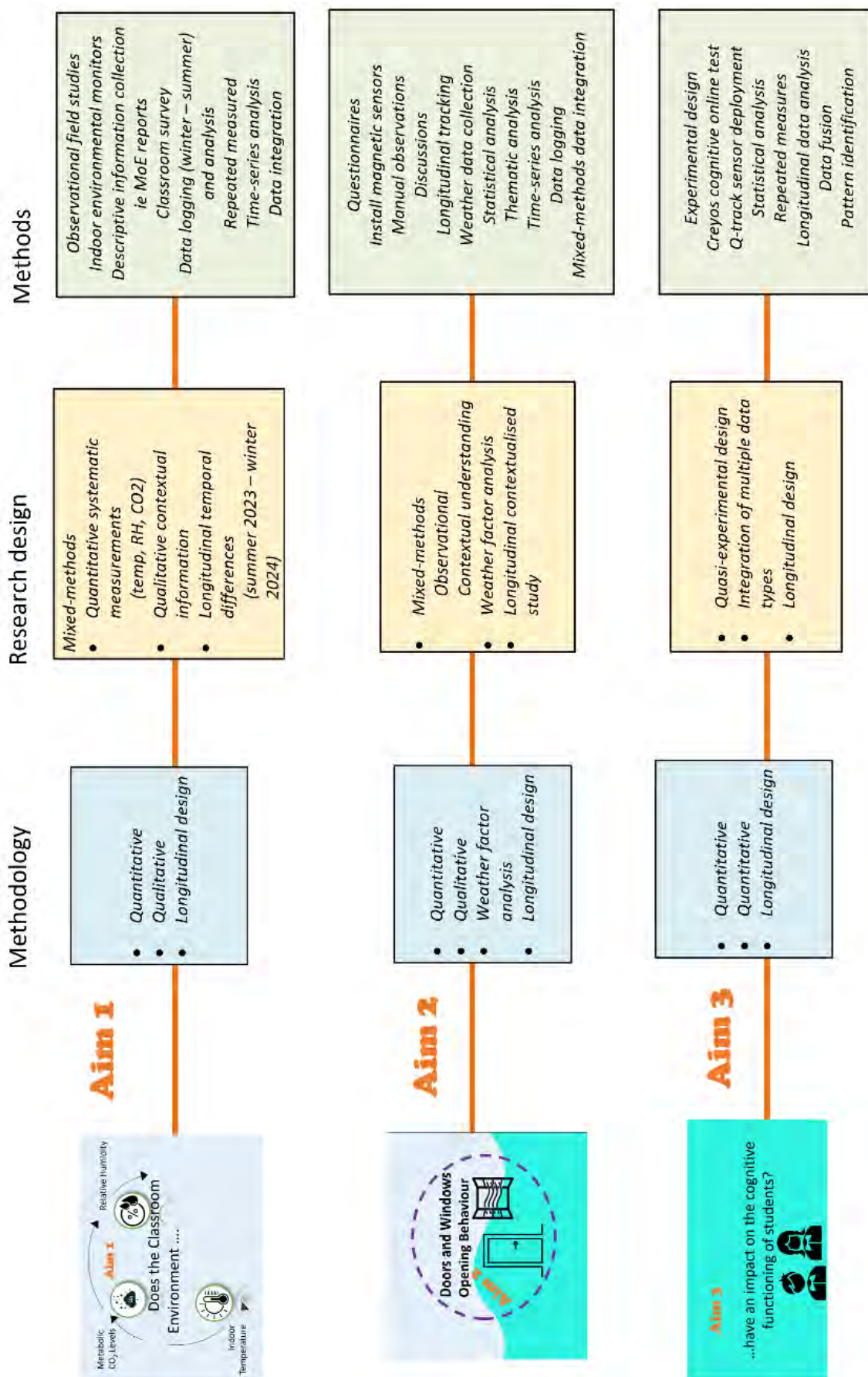
METHODOLOGY

4.1 Introduction

This chapter outlines the methodological framework that underpins the execution and integrity of this research. **Figure 4.1** illustrates the schematic flow and detailed content, setting the stage for a methodological explanation. Initially, the chapter dissects the research problems identified, laying a foundation for a nuanced understanding. This examination transitions into a discussion of the research paradigm and philosophical perspectives that inform and guide the inquiry, providing a lens through which research questions can be viewed and addressed.

Subsequent sections will describe research design and methods, encompassing sampling strategies, data collection and analysis procedures, variables, and measurements, all instrumental in empirically assessing IEQ and understanding the human elements entwined with these conditions. Ethical considerations are outlined to ensure transparency and feasibility. The chapter concludes with an exploration of the pilot study and its preliminary results, which provides a basis for future research activities.

FIGURE 4.1: Structure of Chapter 4



4.1.1 Flow of Chapter 4

With the rationale for the methodological choice firmly established, Chapter 4 unfolds progressively, each section constructing the next in a logical sequence that mirrors the mixed-method approach as outlined in **Figures 4.1**:

1. The **analysis of the research problems** section thoroughly investigates the identified issues, considering the scope and implications for IEQ, teacher practices, and student cognition - the 'what' is happening.
2. In discussing the **research paradigm** and **methodology**, we dive into the philosophical stances—realism and interpretivism—that ground our understanding of reality and knowledge, contextualising how these views integrate to form a coherent research approach, the why it matters.
3. The section on **research design** concretises the practical application of the mixed methods strategy, detailing specific sampling strategies and data collection techniques. This workflow encapsulates the entire spectrum, from empirical IEQ measurements to qualitative exploration of cognitive effects.

The study employs a mixed methods approach to provide comprehensive environmental measurements and explore behaviours and cognitive outcomes. This approach combines quantitative data, providing objective clarity and generalisability, with qualitative inquiry, capturing contextualised human experiences (Guba, Lincoln, et al., 1994). This combination enhances understanding, allowing numerical precision to intersect with interpretive insights, thus enriching the research findings.

Integrating diverse data types leads to a more profound, triangulated understanding of how student experiences influence educational spaces. By aligning the methodological approach with the research questions, this study justifies the selection of mixed methods as a strategy that takes advantage of each strengths.

4.2 Establishing the research paradigm

Research is a systematic and organised process that individuals undertake to discover, understand, and contribute to knowledge within a particular field (Friedman, 2014). According to the Merriam-Webster Online Dictionary (Merriam-Webster, n.d.), the

word research is derived from Middle French “recherche”, which means ‘to go about seeking’. The term itself is derived from the Old French term ‘recherche’, a compound word from ‘re’ and ‘cherchier’. With the aid of lexicology, the word research has two parts: re (again) and search (find), which denotes that we are undertaking a repeatable activity or looking for something new. As Willig (2015) succinctly describes, research is a careful and deliberate endeavour to increase understanding and generate new insights (Berliner, 2002).

A *research paradigm* is a framework that guides research planning, execution, and interpretation by providing shared beliefs and assumptions (Berliner, 2002; Burke and Soffa, 2018). It influences how reality is perceived, knowledge is defined, and studies are conducted (Kivunja and Kuyini, 2017). The critical components of a research paradigm include ontology, epistemology, and methodology (Berliner, 2002; Burke and Soffa, 2018; Siegel, 2006).

To determine the philosophical basis of the research, it is crucial to examine its ontological, epistemological, and philosophical foundations in **Sections 4.3.1 - 4.3.3**. Establishing the research background within the relevant research paradigm is essential. **The chosen paradigm impacts both methodology and research methods.** The research problem’s nature is a key factor in selecting the paradigm, as discussed by Easterby-Smith et al. (2002).

4.2.1 Philosophical background

In philosophical inquiry, knowledge is synthesised by evaluating facts, theories, alternatives, and ideals against each other (Berliner, 2002; Magrini, 2010). According to Barz (2017) and Magrini (2010), philosophical thinking includes examining reality, reflecting on ethics and values, engaging with logic and critical thinking, exploring intangible concepts, considering abstract problems and rationality based on reason and argumentation.

Philosophical attitudes shape knowledge creation and action approaches, influenced by cultural contexts and sociological background (Easterby-Smith et al., 2002; Knez and Thorsson, 2006). Individuals inherit conceptual and observational frameworks that affect their interpretations and distinctions (Easterby-Smith et al., 2002). Research orientations are related to philosophical tendencies, shaped by collective

histories and cultural traditions, but not strictly determined by them (Easterby-Smith et al., 2002; Knez and Thorsson, 2006). Selective abstraction and interpretation are inherent in knowledge creation (Lindgren et al., 2020). Research should avoid favouring a specific philosophical position; the problem nature should dictate the solution method. In knowledge creation, considering alternatives and verifying their superiority is crucial (Casad and Luebering, 2024; Lindgren et al., 2020).

Phenomenology explores the conscious experience and consciousness structures, focussing on subjective experiences in first person (Burke and Soffa, 2018; Easterby-Smith et al., 2002; Siegel, 2006). It delves into metaphysical questions about consciousness, existence, and reality, examining how individuals perceive the world (Burke and Soffa, 2018). Phenomenological research, typically qualitative, aims to capture the depth of subjective experiences and uncover their essence (Creswell et al., 2009; Guba, Lincoln, et al., 1994; Willig, 2015). Researchers use exploration, description, and interpretation to reveal structures of consciousness. Phenomenological approaches include bracketing, reduction, existential, and intentional aspects.

The research objectives outlined in Chapter 1 require exploring philosophical approaches beyond phenomenology. Considering the opposite, more quantitative and positivistic methods (Howe, 2009), focusing on measurable phenomena instead of subjective experiences, are necessary for this study.

When investigating IEQ and cognitive aspects, it is crucial to recognise differences in knowledge perceptions between researchers and practitioners (Easterby-Smith et al., 2002; Magrini, 2010). The study aims to investigate the relationship between IEQ and cognitive functioning in primary school children, which requires a combination of philosophical perspectives to achieve its goals effectively. Using logical positivist and quantitative approaches for data collection, including measurements of air quality and cognitive function, is crucial to address multiple goals (Howe, 2009). Combining experimental, logical positivist, quantitative and survey methods will be essential to achieve research objectives.

4.2.2 Ontological background

Ontology in metaphysics studies is the nature, existence, and reality, exploring the nature of entities and their interactions and relationships (Crotty, 1998; Scotland, 2012). It delves into causation, dependence, and identity, questioning the distinction between appearances and actuality (Burke and Soffa, 2018).

Realism and anti-realism are contrasting ontological positions. Realism posits an independent reality, while antirealism suggests that reality depends on human perceptions or beliefs (Burke and Soffa, 2018; Scotland, 2012).

Different philosophical frameworks, whether realist or nominalist, approach ontology differently. Some assert the objective existence of entities (realist), while others suggest only specific instances are real (nominalist) (Burke and Soffa, 2018; Crotty, 1998). Philosophical perspectives vary within these frameworks, such as Analytic vs. Buddhist and Aristotelian vs. Logical Positivism.

Aims 1 and 3 align with logical positivism principles focusing on empirical observation and measurement. However, aim 2, adopts a phenomenological approach that emphasises subjective experiences and contextual meanings. By studying teachers' window-opening behaviour, insights into IEQ and thermal comfort factors are gained. Combining logical positivism and phenomenology involves collecting objective data while exploring subjective interpretations. This interdisciplinary study aims to understand both objective and subjective dimensions in a comprehensive way. Examining teachers' behaviours enhances the phenomenological perspective, offering insights into human experiences in the school environment. The research was carried out within the frameworks of logical positivism and phenomenological ontology.

4.2.3 Epistemological background

Epistemology explores how individuals acquire knowledge and understand the world (Siegel, 2006). It delves into the connection between the knower and knowledge, questioning how beliefs shape understanding (Crotty, 1998; Denzin and Lincoln, 2011). The epistemological inquiry examines the validation and trustworthiness of knowledge (Easterby-Smith et al., 2002; Magrini, 2010). Various epistemological constructs include Constructivism, Empiricism, Foundationalism, and Pragmatism.

Knowledge creation involves abstraction, identification, and recombination, urging researchers to be mindful of their claims (Cohen et al., 2002).

Naturalised epistemology integrates scientific knowledge with everyday experiences by combining quantitative measurements with qualitative insights into individuals' lived experiences (**Aim 1 and 3**). **Constructivism** acknowledges the contextual influence on perceptions and behaviours, which is crucial to understanding teachers' actions in indoor environments. Teachers may adjust behaviour based on perceived effects on the learning environment (**Aim 2**). The research methodology encompasses experimental, logical positivism, quantitative, and survey research. The ontological and epistemological approaches combine logical positivism with phenomenology and constructivism with naturalism, respectively.

4.2.4 Summary of research paradigm

The PI has adopted a mixed methods approach, combining quantitative and qualitative data collection and analysis methods (Creswell et al., 2009; Guba, Lincoln, et al., 1994). The methodology for each aim illustrates the use of quantitative measurements and qualitative contextual information, supporting a mixed-methods design (Creswell et al., 2009). The approach leverages quantitative data for generalisability and qualitative data for depth and context, enhancing the study's robustness in understanding complex research phenomena (Creswell et al., 2009). Aligning the research design with the multifaceted nature of the study's questions through a mixed-methods framework is crucial, given the interdisciplinary and intricate aspects of the research (Creswell et al., 2009).

4.3 Research Methodology

The methodology of a research study acts as the bridge that connects ontology, epistemology, and operational guidelines for research (Burke and Soffa, 2018; Easterby-Smith et al., 2002). It outlines the principles and procedures that guide scientific investigations, converting philosophical foundations into actionable research strategies (Burke and Soffa, 2018; Scotland, 2012). Methodology encompasses various components such as philosophy, approaches, strategies, methods, choices, timeframes, and data analysis techniques (Burke and Soffa, 2018; Cohen et al., 2002). Creswell (2021) underscores key considerations when selecting

a research methodology, prioritising the research problem over methodological constraints to comprehensively address research complexities.

Moving from theory to application, the methodology section transitions into the concrete elements of the research design, manifesting theoretical concepts into practical research steps. This alignment between theoretical principles and methodological practice in research design and implementation ensures a cohesive academic inquiry (Creswell, 2021).

Building upon the research framework depicted in Figure 4.1, this section will elucidate the research design and methods employed.

Research design is a foundational strategy that guides data collection, analysis, and interpretation in a study, intrinsically related to the broader concept of research methodology. This synergy between design and methodology requires adjustments to maintain the integrity of the study (Burke and Soffa, 2018; Easterby-Smith et al., 2002).

The subsequent sections will provide a detailed account of the research design, starting with an overview of the research design and methods, then data collection and measurement techniques, and concluding with the data analysis plan. For clarity and coherence, each aim will be presented its corresponding data collection and analysis subsection.

Nevertheless, several issues universally apply to all sections, which will be addressed herein. This pertains to:

4.3.1 Weather stations

NIWA maintains a network of air monitoring stations nationwide. The geographical coordinates of the weather stations closest to the studied primary schools are detailed in **Table 4.1**. For schools in Auckland, three different weather stations are used because of the study's scope. Access to pertinent data from these stations is facilitated through the CliFlo National Climate Database online (National Institute of Water and Atmospheric Research (NIWA), 2021).

TABLE 4.1: *Weather Stations Used for Ambient Data*

Region	Station Name	Latitude	Longitude
Auckland	Kauri Point	-36.812	174.707
Auckland	CW4778 Auckland	-36.863	174.739
Auckland	EW0594 Auckland	-36.909	174.771
Hawke's Bay	Hawke's Bay Station	-39.49846	176.91189
Christchurch	Kyle St Station	-43.53074	172.60769
Dunedin	Musselburgh Station	-45.90129	170.5147

4.3.2 School terms and operating hours

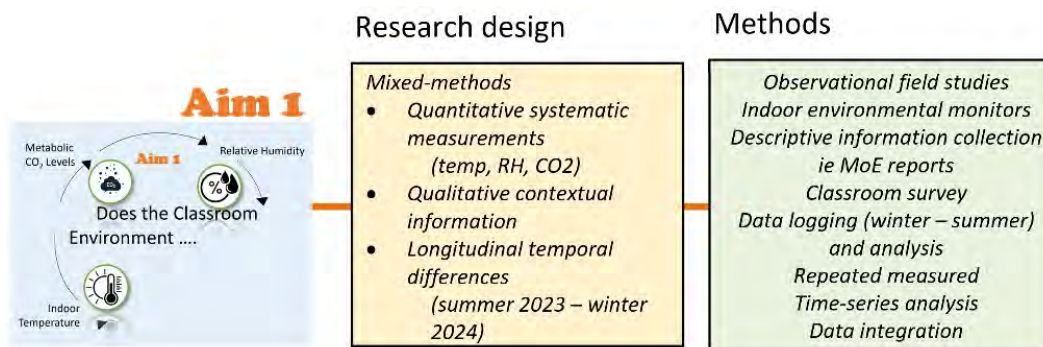
In NZ, schools follow a four-term schedule from February to November, each lasting 10-11 weeks and separated by a two-week break, except for the extended break between Term 4 and Term 1 of the following year. Terms 2 and 3 cover the winter months of June, July and August, with primary school classes held from 9:00 to 15:00, Monday to Friday. The data presented only details operating hours (students in school, not weekends or school holidays).

Referring to **Appendix D**, **Table D.1** specifies the weeks selected for the 2nd deployment study, strategically chosen to align with the school calendar and various activities. This selection maximises data collection opportunities and accurately captures student experiences and behaviours throughout the academic year.

4.3.3 Aim 1 - Research Design and Methods

The research design depicted in **Figure 4.2** aims to establish a foundational knowledge of the parameters of Indoor Environmental Quality (IEQ) in primary schools in NZ. This descriptive cross-sectional survey employs a longitudinal approach for seasonal data collection.

FIGURE 4.2: Aim 1 - Research design and methods



The study adopts a hybrid approach, combining quantitative systematic measurements using standardised IEM technology to assess thermal comfort, RH, and CO₂ levels for ventilation quantification. Data aggregation from various classrooms at predefined intervals aims to build a comprehensive IEQ profile with added qualitative contextual insights such as occupancy patterns.

Furthermore, a longitudinal strategy monitors environmental conditions across contrasting seasons, winter and summer, uncovering the variables' dynamics and seasonal impacts on IEQ.

For **Aim 1**, the research methodology to analyse the levels of thermal comfort and CO₂ incorporates a mixed method approach, which includes the following.

- Quantitative Measurements (Observational Field Research)
- Qualitative Contextual Information (Descriptive)
- Longitudinal Design

Before installation in classrooms, the IEMs underwent co-location calibration at Massey University's Indoor Air Laboratory for two weeks to ensure accurate environmental readings (**Figure 4.3**). Experts carefully adjusted key factors like temperature, RH, and CO₂ levels to simulate classroom conditions accurately post-deployment for optimal performance.

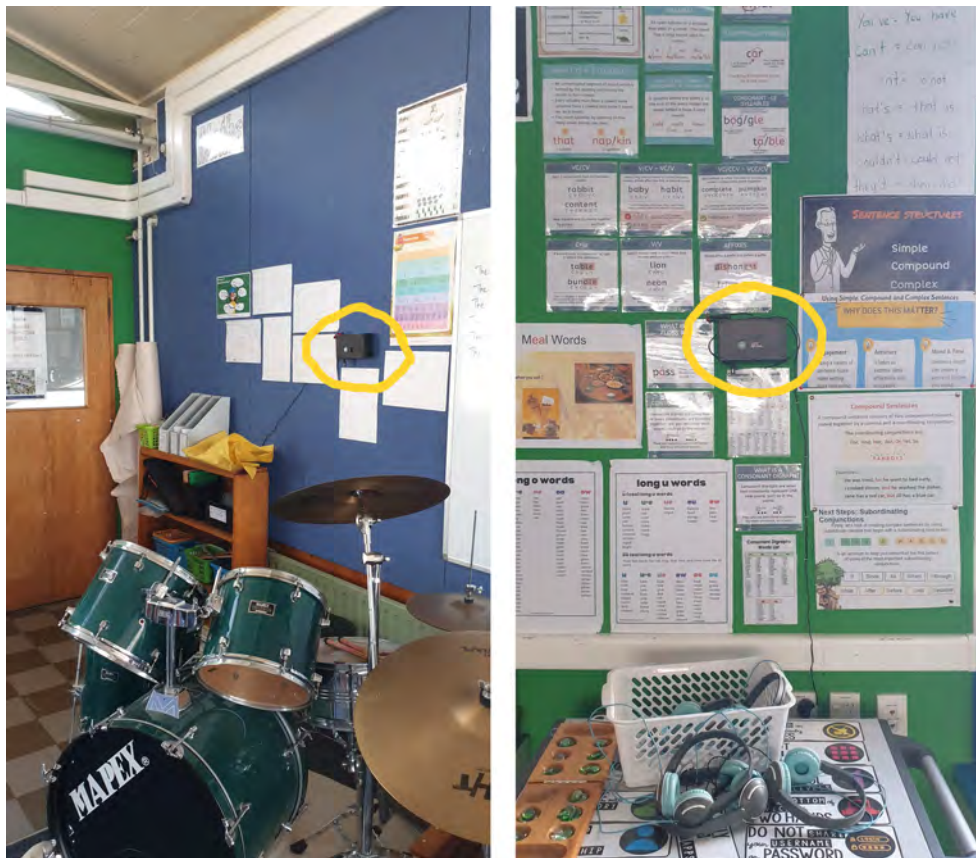
FIGURE 4.3: Co-location Calibration of IEM



Calibrating temperature, RH and CO₂ levels ensured precise tracking in indoor conditions, maintaining comfort, air quality, and effectiveness of ventilation. The two-week calibration process rigorously tested and adjusted the IEM units to guarantee reliable air quality data collection.

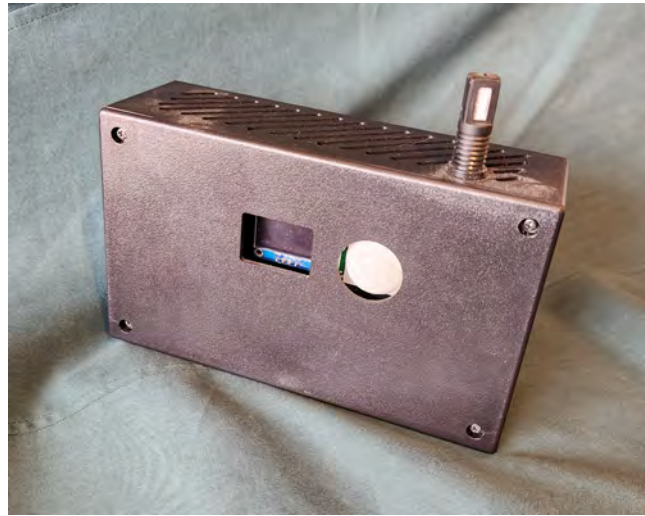
To gather data on TC and metabolic CO₂ levels in classrooms, observational field studies will be carried out using the IEM platform (**Figure 4.4**). Additional investigation through classroom surveys will assess window operability, heating systems, and ventilation types in each classroom.

Focussing on selected classrooms in School 1 (S1-1 to S1-6), the study will track the levels of TC and CO₂ over time. Daily data collection from March 2023 to June 2024 will identify trends, based on a preliminary study involving three classrooms from March to July 2023. The IEMs placed approximately 1.5 m from the floor will monitor environmental conditions without disrupting classroom activities (**Figure 4.4**).

FIGURE 4.4: *Position of IEM in Classrooms*

Instrumentation - SKOMOBO vs other IEMs

In response to limited options for integrated environmental monitors (IEMs) to track multiple variables in 2017, a collaboration between Massey University and NIWA developed the SKOMOBO monitoring platform (**Figure 4.5**).

FIGURE 4.5: *The New Version of SKOMOBO*

Source: Authors own

The name SKOMOBO, an acronym for **SKO**ol **MO**nitoring **BO**x. The acronym represents its focus on school environments, offering a tailored solution catering to educational settings' unique challenges. Choosing commercial alternatives over commercial alternatives, SKOMOBO provided cost-effective benefits and supported innovative academic initiatives within the university (Boulic et al., 2024).

The consistent installation, data collection, and analysis protocols for all IEM deployments were monitored by Dr. Boulic, ensuring methodological rigour and standardisation throughout research activities (Boulic et al., 2024).

Sensors employed

PI joined the team working with IEM after the initial model had already been manufactured. Consequently, the method section will focus on detailing the sensors incorporated in the design rather than explaining the rationale behind their selection.

The sensors embedded in the SKOMOBO monitoring platform (**Table 4.2**) include the TELAiRE 9602-3-D-1 for temperature and RH measurement, chosen for its accurate polymer technology in RH measurement and PTAT methodology for temperature detection (Y. Wang et al., 2017). For CO₂ monitoring, the SenseAir K30 sensor was selected due to its robustness and precision in measuring CO₂

concentrations (Y. Wang et al., 2017).

Using the CO₂ decay method, the SenseAir K30 sensor estimates ventilation rates in classrooms, aiding in assessing air exchange efficiency and IAQ (Bennett et al., 2019; Y. Wang et al., 2017).

Table 4.2 details the sensors embedded in SKOMOBO.

TABLE 4.2: *Specifications of the Selected Sensors for SKOMOBO*

Sensors		
Features	TELAiRE 9602-3-D-1	SenseAir K30 STA
Measurement	Temperature and RH	Carbon dioxide (CO ₂)
Range	Temperature: -20 °C to 70 °C; RH: 0% to 100%	0 to 5000 ppm vol
Accuracy	Temperature: ±0.5 °C; RH: ±2% (20 to 80% RH), and RH ±3.5% (0% to 20% RH and 80% to 100% RH)	±30 ppm or ±3% of reading

The study confirms the reliability of SKOMOBO in temperature, RH, and CO₂ level measurements, with rapid response to environmental changes similar to commercial models such as TSI Qtrak (Boulic et al., 2024).

As a result of the work carried out by the team with SKOMOBO, the following **awards have been received:**

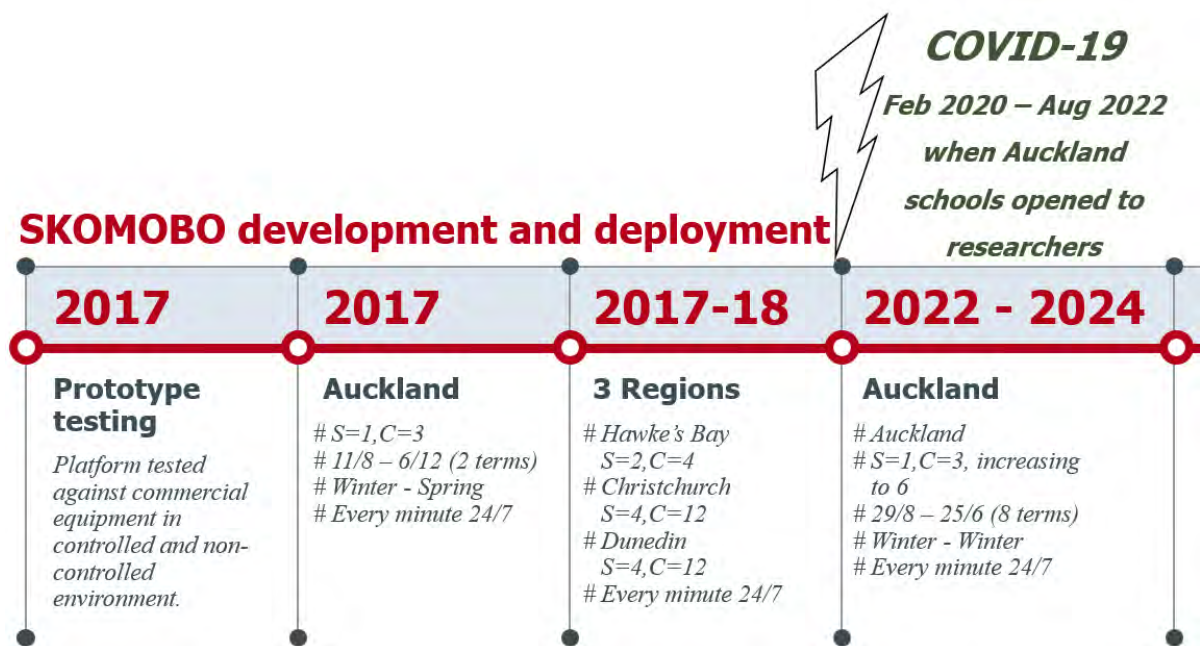
1. The SKOMOBO research team was awarded Best Emerging Technology at an Innovation Showcase event in Auckland in 2018
2. The SKOMOBO research team was awarded the Innovation Award at the 2018 NZ Building Industry Awards
3. Research Team of the Year – RICS 2021 NZ Awards

This IEM (SKOMOBO) will be used throughout the study, supporting Aim 2 and Aim 3.

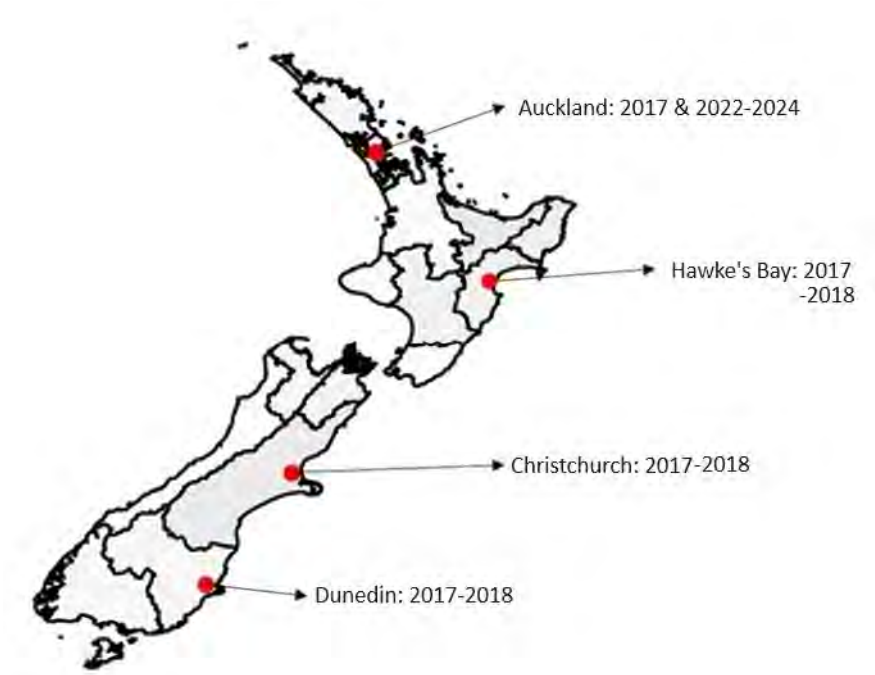
Data collection - deployment of IEM

Figure 4.6 provides an overview of the various deployments explored throughout this study.

FIGURE 4.6: Timeline of IEM Development and Deployment over North and South Island



The IEM deployment **Figure 4.6** followed a phased strategic approach, starting with a pilot test in a primary school near Massey University's Auckland campus to validate the prototype before a wider distribution. Subsequent installations spanned Hawke's Bay, Christchurch, and Dunedin to capture NZ's climatic diversity and urban-provincial mix (**Figure 4.7**). The PI contributed as a research assistant in these deployments, which occurred before the COVID-19 pandemic.

FIGURE 4.7: *New Zealand Detailing Initial Deployments of IEM*

An additional deployment (by the PI as a doctoral study) in an Auckland school occurred after mid-2022, coinciding with the relaxation of COVID-19 protocols in Auckland schools.

Duplicate IEM installations in each region ensure quality assurance through redundancy, data cross-verification, and calibration error detection. This practice improves the reliability and precision of environmental data monitoring, promoting effective indoor environmental quality management (Nowell et al., 2017; Maag et al., 2018; Nalakurthi et al., 2024).

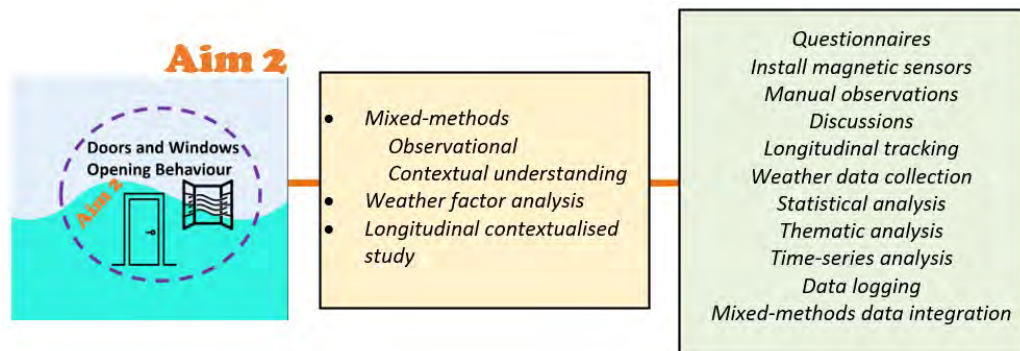
Data analysis

The effects of interaction between the variables are analysed using the R programming environment (R Core Team, 2021).

4.3.4 Aim 2 - Research design and methods

The research framework depicted in **Figure 4.8** illustrates an explanatory, mixed-method design to discover classroom window and door operation patterns influenced by weather factors over an extended period.

FIGURE 4.8: Aim 2 - Research design and methods



The **explanatory design** delves into the reasons and predictors behind specific behaviours, going beyond a mere description to provide explanations. The **mixed methods approach** combines quantitative data (e.g. sensor recorded window / door operations and meteorological data) with qualitative data (from observations and surveys) for a comprehensive understanding of behaviours and their drivers.

Integrating diverse data types, this design for Aim 2 illuminates the complex factors influencing classroom ventilation behaviours, blending human behaviour aspects with environmental conditions through a mixed-methods approach encompassing quantitative observations, qualitative insights, weather analysis, and a longitudinal contextual design.

An array of **methods** will be employed, including:

- **Sensor deployment:** Magnetic sensors in windows and doors at School 1 automatically capture open/close movements (**Figure 4.9**). Initially installed in S1-1 to S1-3, it was extended to other classrooms with additional funding.

FIGURE 4.9: Placement of sensors



- **Random observation sessions:** Unannounced observations at School 1 supplement sensor data, capturing contextual factors potentially missed.
- **Questionnaires:** Surveys distributed to teachers at School 1 to collect self-reported practices and perspectives on window/door use.
- **Meteorological data logging:** Obtaining atmospheric data (temperature, humidity, and windspeed) from nearby stations.
- **Longitudinal tracking:** Monitoring of the same classrooms in School 1 during seasons or academic years for weather-induced behaviour changes.
- **Trend analysis over time:** Using time-series statistical methods to analyse data for trends, cyclical patterns, and temporal effects.

Observation studies complement magnetic sensor data in TC&V research by offering contextual understanding, insights into user behaviour, sensor verification, adaptation strategies assessment, education, and feedback provision. Although sensors provide quantitative data, observations offer qualitative perspectives on the use and efficacy of ventilation strategies in creating a comfortable learning environment.

The primary objective of deploying magnetic sensors is to effectively study teachers' and students' ventilation behaviours. These sensors enable precise monitoring,

non-intrusive data collection, real-time analysis, long-term monitoring, and improved environmental health. By incorporating magnetic sensors, the study aims to achieve detailed insights into natural ventilation patterns, real-time monitoring capabilities, and long-term trend identification, significantly advancing TC&V knowledge and improving IEQ.

Instrumentation - observation form

An observation form (**Figure 4.10**) was used to document the status of the door / window in each uniquely identified room. Visual observations gauged space characteristics and disentangled the factors influencing window/door operations.

Teachers indicated student involvement in window management, prompting the categorisation of reasons for window adjustments into occupancy, Indoor Environmental Quality (IEQ), or external factors. Unclear adjustments were clarified after the session to minimise interruptions.

Photographs were taken during observation studies to:

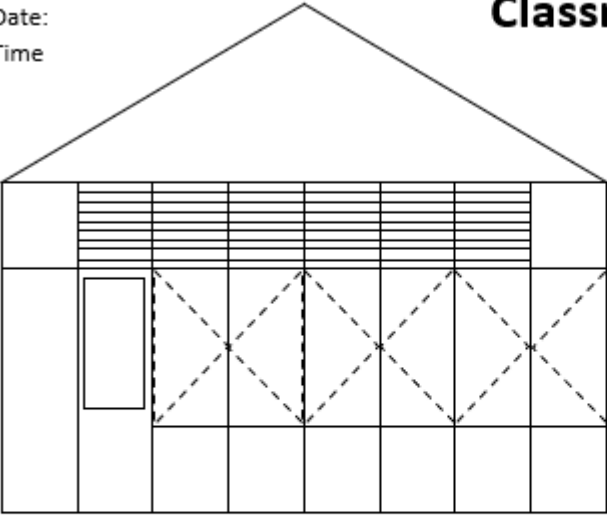
1. Provide concrete evidence of window usage patterns, complementing survey data.
2. Facilitate comparative analysis of behaviour under varying conditions and times.
3. Enhance your understanding of the context, offering nuanced details beyond written records.
4. Capture natural behaviour non-intrusively, avoiding observer influence on actions.

Combined with recorded meteorological data, these photographs offer a comprehensive view of the factors that influence window-opening patterns.

FIGURE 4.10: Observation Survey Sheet

Day: _____
Date: _____
Time: _____

Classrooms



Back casement windows
Open ☐
Closed ☐

Occupancy pattern -

☐ Occupied ☐ Not occupied ☐ On lunch/tea break ☐ At the pool ☐ Gone to assembly ☐ Other

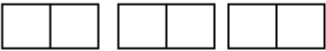
Type of activity

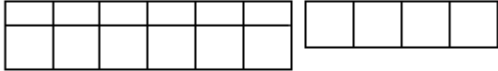
☐ Sedentary (seated) ☐ Active (Running playing)

Library

Louvers 

3 Doors 

3 Front windows 

10 Back windows 

Occupancy pattern -

☐ Occupied ☐ Not occupied ☐ On lunch/tea break ☐ At the pool ☐ Gone to assembly ☐ Other

Type of activity

☐ Sedentary (seated) ☐ Active (Running playing)

Computer weather status and temp

Instrumentation - magnetic window sensors

The Minew S1 window sensors (**Figure 4.11** left side) utilised in this study are specifically designed to detect window opening and closing without need for calibration. These sensors operate reliably out of the box, offering a binary function of open or closed status.

FIGURE 4.11: Minew Sensor (left) and Gateway Instrument (right)



The technical specifications for the Minew S1 Window Sensor are as follows:

- Dimensions: 50 mm x 35 mm x 15 mm
- Weight: 30 grams
- Battery life: Up to 2 years
- Communication protocol: Bluetooth Low Energy (BLE) 4.0
- Detection range: Up to 50 m
- Operating temperature: -10 °C to 50 °C
- Operating humidity: 0% to 95% relative humidity
- Power supply: CR2032 coin battery
- Sensor type: Magnetic switch sensor

The study also incorporated the Minew Gateway (**Figure 4.11** right side), a key element in centralising sensor data for efficient data collection. The technical specifications for the Minew G1 gateway are as follows.

Dimensions: 100 mm x 100 mm x 20 mm
Weight: 150 grams
Power supply: DC 5V/2A via Micro USB
Communication protocols: BLE 4.0, Wi-Fi 802.11
b/g/n 2.4 GHz
Coverage range: Up to 100 m
Data rate: BLE 1Mbit/s
Operating temperature: -10 °C to 50 °C
Operating humidity: 0% to 95% relative humidity
Data storage: Cloud storage with real-time data
transmission

The Minew sensors offer high accuracy and sensitivity in detecting window states, ensuring reliable monitoring of natural ventilation changes and capturing detailed ventilation patterns for understanding their impact on thermal comfort in classroom settings.

Deployment

The sensors were installed in classrooms S1-1 to S1-3 with a Minew G1 Gateway per classroom for comprehensive data collection on window states affecting TC&V analysis.

Gateway setup involved connecting Minew G1 gateways to the school's Wi-Fi network for uninterrupted internet access and pairing each gateway with nearby sensors to ensure seamless data flow.

Due to cost constraints, data management opted for a USB-based local data collection method, leveraging RStudio for analysis, deviating from a cloud-based solution.

Key advantages included easy deployment for widespread installation, long sensor battery life for less maintenance, and consistent data collection over extended periods.

Efficient data collection from sensors involved careful installation, robust gateway setup for reliable communication, instantaneous data transmission on status changes, USB-based local storage, and periodic retrieval for secure and efficient data

management.

The G1 gateway served as the central data collection hub, aggregating sensor information on window status and providing extended coverage through strategically placed gateways for comprehensive data collection.

In general, integrating sensors, G1 gateways, and local data storage provided a cost-effective framework for data collection, ensuring data integrity and security, critical to improving the primary school learning environment.

Data flow process

The data flow process between sensors and G1 gateways is illustrated in **Figure 4.12**, portraying:

1. Sensors detecting window positions and transmitting data via BLE to the corresponding G1 gateways.
2. Gateways directly transmit collected data to a connected device (USB).

FIGURE 4.12: *Minew Sensor and Gateway Data Flow Process*



Monitoring and maintenance practices involve:

- Regular checks on Minew G1 Gateways to ensure consistent connectivity and accurate data transmission.
- Prompt troubleshooting of connectivity or transmission issues to maintain a continuous and precise data flow.

Data collection - teachers questionnaires

The initial survey was conducted in Auckland in 2015 as part of a Bachelor of Construction final year research project, under the supervision of Dr. Boulic. The methodology was chosen for its reliability and was later expanded in 2017 to include cities on the South Island, monitored by Dr. Boulic and assisted by the research assistant. This expansion helped maintain standardisation of tools and methodologies, improving consistency between studies and minimising bias, as demonstrated in **Figure 4.13**.

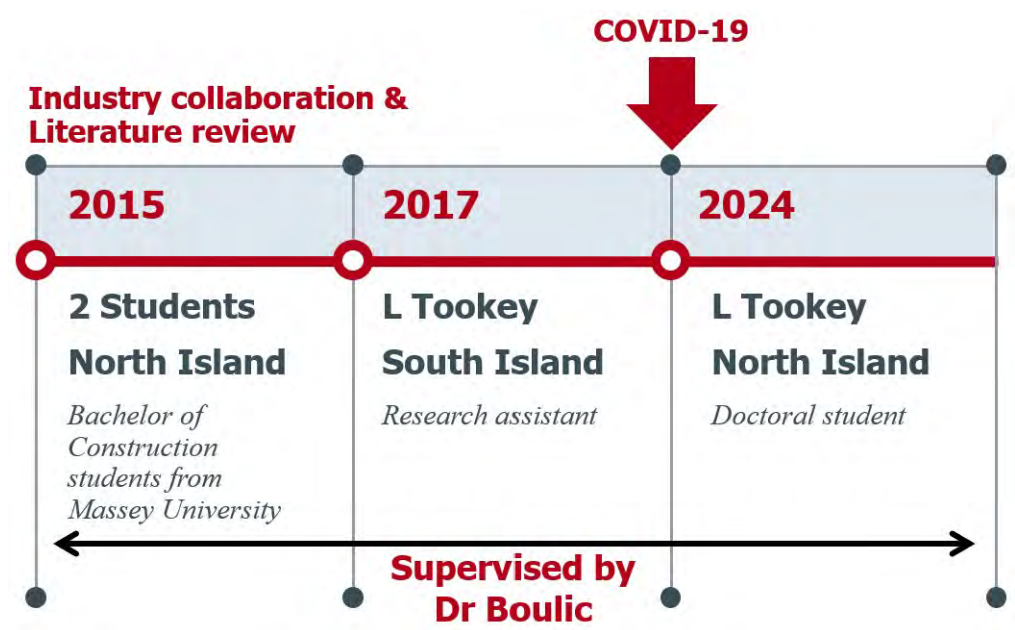
With the proven effectiveness of this approach, it was naturally carried forward to the 2024 study in Auckland schools, where the PI for the doctoral research utilized the same methodology. This ensures robust comparability and reproducibility of the results in different locations and time periods.

This approach not only honours the foundational work done in prior studies but also contributes to a more robust influence on findings across multiple cohorts. The PI believes that the decision to use a self-administered survey was rooted in its several distinct advantages as a data collection tool (<empty citation>). One significant reason for this choice is that self-administered surveys can enhance the accuracy of responses by allowing participants to reflect on their responses without the influence of an interviewer. This format can lead to greater honesty in responses, particularly on sensitive topics, as the respondent may feel more comfortable providing their views in a private setting.

Furthermore, self-administered surveys are highly efficient in terms of time and resources, especially when working with a larger sample of teachers (2015 sample) **Figure 4.13**. This method allows for the simultaneous collection of data from multiple participants without the logistical constraints associated with in-person interviews (2015 sample). Given that the research involved the participation of a dispersed sample (2017 sample) **Figure 4.13** of educators, the online survey format allowed the researcher to reach a wider audience quickly and effectively. To avoid bias in answering the questionnaire, due to the close working relationship developed with the teachers, the PI decided to continue the same format (self-administered surveys) for the study in 2024 (<empty citation>).

In summary, the choice of a self-administered survey was deliberate, aimed at maximising data accuracy, efficiency, and comparability with existing research.

FIGURE 4.13: *Development and Disbursement of Questionnaire over North and South Island*

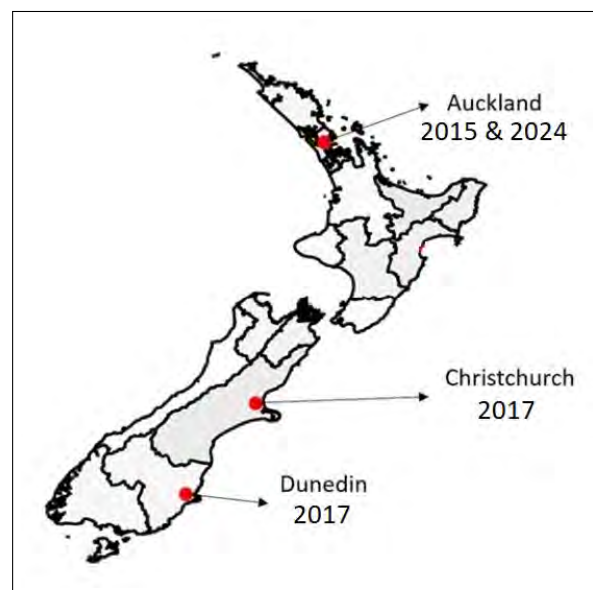


Data collection involved self-administered questionnaires in various formats, as detailed in **Table 4.3**, reaching 92 schoolteachers in 38 Auckland primary schools in 2015, 35 teachers in Christchurch and Dunedin in 2017, and two Auckland schools in 2024. The geographical locations of the schools were carefully depicted and managed sensitively (**Figure 4.14**).

TABLE 4.3: *Summary of Disbursement and Collection Methods of Teachers Survey over Three Distinct Survey Years*

Year	Deployment method	Collection method
2015	Hand delivered	Collected by hand or prepaid return envelope
2017	Email via internal school internal	Email
2024	Online survey tool - link sent via School Principal to all teachers	Online survey tool

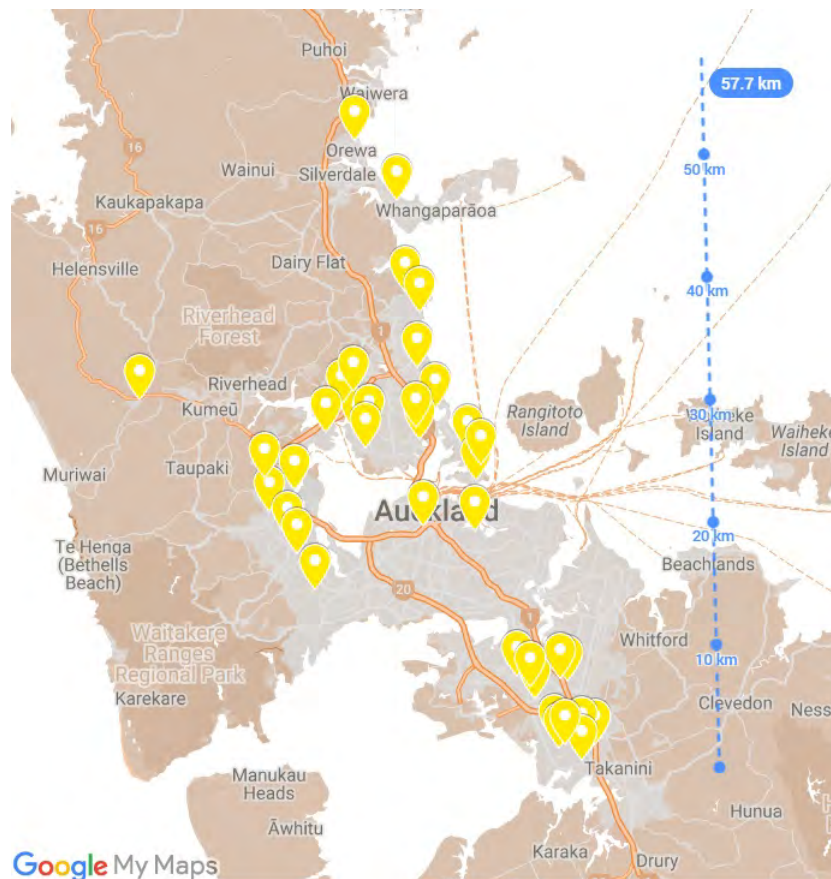
FIGURE 4.14: *Three Cities in NZ where Questionnaires were Circulated*



Source: <https://www.worldatlas.com/maps/new-zealand>

In Auckland, the 38 schools participating in the 2015 survey spanned approximately 54 km North-South, 47 km East-West, and 29 km South-West, as shown in **Figure 4.15**. The geographic details of the schools in Christchurch, Dunedin, and Auckland in 2024 were omitted for sample size and institutional confidentiality reasons.

FIGURE 4.15: *Location of 38 Schools in Auckland*



<https://www.google.com/maps>

Data collection - observation forms

Structured training and calibration procedures were implemented to ensure consistency and reliability in data collection by a single observer (PI). Strategies included training the observer, standardising the observation process, creating a coding manual, pilot testing, self-monitoring, and maintaining an observer log to enhance data validity and internal reliability.

To mitigate observer bias, the PI incorporated transparent reporting within the dissertation and triangulation with magnetic sensor data to provide additional

validation beyond subjective observation. These steps reinforce the credibility of the research and ensure a trustworthy representation of the phenomena of the study.

The data recording and notation system, crucial for accurate analysis, detailed specific aspects that the PI noted: - Temporal data recorded at 20-minute intervals with precise time stamps. - Window and door details, including binary open/closed status, mechanism type, cardinal direction, and human factors such as occupancy and space purpose. - Document anomalies, take timestamped photographs, and include subjective observer notes for contextualising data (**Figure 6.16** to **Figure 6.18**).

Data collection - magnetic window sensors

Data were collected according to the specifications outlined in **Tables D.3** to **D.6**, detailing the dates from Term 1, 2023, to Term 2, 2024. The sensors were configured to record status changes every 5 seconds. This high-resolution data is being shared with another doctoral student using it for machine learning applications.

Data analysis - teachers questionnaire

The evaluation of questionnaire data will encompass a multistage process using statistical techniques to ensure the reliability and validity of the conclusions.

Upon collection, the questionnaire data was digitised, imported into R (version 2023.12.1) (R Core Team, 2021) for analysis, the precision was verified and a multistep cleaning process was performed. This involved identifying missing values and correcting errors to maintain data integrity.

- There were only three instances of this in all the questionnaires received. Initially **incomplete questionnaire responses** were flagged. Where possible, teachers were contacted and corrections were made. If contact could not be made and missing values not rectified - only one instance **missing values** were addressed through imputation techniques if deemed suitable or otherwise listed for exclusion in subsequent statistical analyses to prevent results distortion (McNeish, 2016; Mirzaei et al., 2022).
- All entries were checked for **input errors**. Inconsistencies were found, such as out-of-range values or impossible data points (e.g., a 'six' on a five-point Likert

scale). They used words instead of numbers, they circled all 5 of the variables on the Likert scale.

The Likert scale and ordinal responses were transformed and recoded for consistency and analytic alignment, while scale validation was performed using Cronbach's alpha. Descriptive statistics helped to understand the characteristics of the data and identify outliers or errors.

The decision to use a Likert scale was based on its effectiveness in measuring attitudes and opinions. These scales allow respondents to express varying degrees of agreement or disagreement with specific statements, which is crucial for capturing the nuances of their feelings.

One advantage is that ordinal data aligns well with the nature of the attitudes being studied. Although we know that "agree" is a higher response than "neutral", we do not need to assume equal intervals between these points. This is particularly relevant when dealing with subjective constructs, where precise numerical differences are not as meaningful.

Using a Likert scale produces data that can be statistically analysed in various ways. Although there is some debate about treating it strictly as interval data, we can still apply means, medians, and modes, as well as nonparametric tests. This versatility helps to draw more comprehensive conclusions from the data.

The simplicity of the Likert scale use is one of its strengths. Respondents find it intuitive to understand and navigate. This ease of use helps to encourage more accurate responses, as they can quickly express their feelings.

While there are limitations, such as the potential for central tendency bias or the challenge of fully capturing the complexity of feelings, the strengths outweigh the concerns for this study. The richness of the data gathered from a range of response options far exceeds what could be gained from a simple yes/no format.

Exploratory Data Analysis (EDA) techniques, including histograms and box plots, will be used to uncover patterns and outliers, guiding further inferential analysis (Critical Data, 2016). Demographic profiling will provide context, with detailed

demographic analysis and heat pump-specific inquiries leading to inferential statistical methods such as the Wilcoxon Signed-Rank Test and Spearman rank correlation coefficient for relationship assessments (Critical Data, 2016; STHDA, 2024).

Data analysis - Observation forms

To ensure the integrity of the findings, the PI used a comprehensive data processing and analysis protocol for the observational and sensor data collected. This involved data cleaning, coding qualitative data, and quantitative analysis with statistical software, creating a reproducible pathway from raw data to meaningful insights.

Observations during school walk-through were transcribed into an Excel spreadsheet every 20 minutes, with variables such as door and window positions coded numerically for statistical analysis. Weighting and aggregation techniques were applied to calculate the count and percentage of doors and windows in different states, providing summary metrics for each room.

An example row (**Figure 4.16**) from the Excel file illustrated the format and data captured during observations, including date/time, room focus, coded door and window positions, and percentage calculations.

FIGURE 4.16: *Example Data Entry from Observation Form*

Date	Time	Room	Front Door	2nd Door	3rd Door	Back Door	Ext Door	Front Win 1	...	% Door Open	% Window Open
23/03/2023	9:00	Library	1	0	0	-	-	0	...	11%	33%
23/03/2023	11:00	Room 5	3	-	-	0	0	2	...	33%	94%

Thematic analysis followed the coding process, identifying patterns and trends through data normalisation, coding refinement, theme identification, and quantitative analysis, ensuring a structured and analysis format to understand environmental and behavioural dynamics in the study setting.

Room identifiers	Window and door positions
Outdoor temperature	Cloud conditions
Relative humidity	Room occupancy status
Reason for the room being empty (if applicable)	

Data analysis - magnetic window sensor data

Integrating observational and sensor data in IEQ research offers a comprehensive understanding of indoor environments, incorporating human behaviours and environmental parameters to reveal deeper insights. Observational data capture human-centric perspectives on interactions with the environment. In contrast, sensor data provides precise measurements of environmental conditions, together painting a holistic picture of the impact of indoor spaces on occupants.

Combining these data types improves the validity of the research by balancing subjective human observations with objective sensor data, leading to more robust conclusions on the influence of environmental factors on occupant well-being in educational settings. In addition, integration facilitates the discovery of hidden patterns and correlations, guiding decisions on space design and management.

During the field study, the PI strategically merged unannounced observational visits with continuous sensor monitoring, aligning data collection timelines for direct comparison. This calibration method validated sensor accuracy, identified discrepancies, and ensured data reliability. The integration process involved various steps, such as data preprocessing, merging, analysis, visualisation, interpretation, and reporting, enhancing the depth and credibility of the research.

The PI implemented data collection, security, backup, metadata management, and archiving practices to ensure effective data management. Detailed documentation, data cleaning procedures, anomaly detection, sensor downtime analysis, and consistency checks were rigorously performed to maintain data integrity and reliability. Data cleaning included duplicate removal, anomaly handling, data imputation, consistency checks, transformation, normalisation, and validation, all documented for transparency and reproducibility.

Data analysis preparation

PI will use statistical software R for data analysis (R Core Team, 2021). Descriptive and inferential statistical analyses will summarize data characteristics and draw population inferences.

Integrating these data management and cleaning procedures will guarantee an accurate, reliable, and well-organised dataset, essential for robust analyses and credible research results.

Sensor data will be validated by combining them with direct observation data, ensuring the accuracy of the collected data to represent real world actions, as indicated in **Table 4.4**.

TABLE 4.4: *Calibration Table: Human-Recorded vs. Sensor-Collected Data*

Window / Time		S1-1			S1-3		
Sensor / position		LT012	LT013	LT014	LT006	LT005	LT004
		L	M	R	L	M	R
10:20	PI	1	1	1	1	0	1
10:20	S	true	true	true	true	false	true
10:40	PI	1	1	1	1	0	1
10:40	S	true	true	true	true	false	true
11:00	PI	1	1	1	1	0	1
11:00	S	true	true	true	true	false	true
11:20	PI	1	1	1	1	1	1
11:20	S	true	true	true	true	true	true
11:40*	PI	0	0	1	1	1	1
11:40*	S	false	false	true	true	true	true

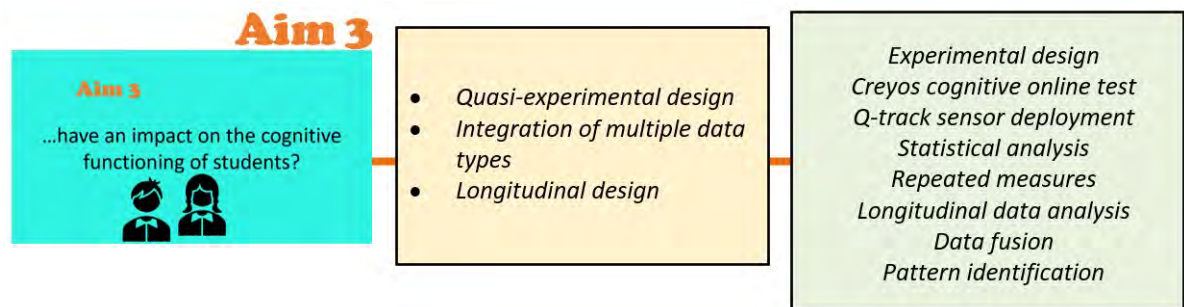
Notes: L = Left; M = Middle; R = Right; 0 = closed; 1 = open;

PI = Principle investigator; S = Sensor;

*Cognitive test = PI closed two of the three windows in Room 1

4.3.5 Aim 3 - Research design and methods

A mixed methods approach for **Aim 3** will blend quasiexperimental and correlational designs with a repeated measures framework to explore interactions between CT, metabolic CO₂ concentrations and cognitive function in educational settings (**Figure 4.17**). The integration of these methodologies allows for both causal inference and statistical relationship assessment within the constraints of the natural classroom environment.

FIGURE 4.17: *Aim 3 - Research design and methods*

The quasiexperimental design will explore cause-and-effect relationships by tracking changes in cognitive function concerning environmental conditions in different classrooms or periods, considering variables such as temperature, RH, and CO₂. The correlational design will uncover statistical connections between TC, CO₂ levels and measures of cognitive function without experimental manipulation.

Implementing a repeated measures design involves administering weekly online cognitive tests to students under varying classroom conditions to track changes over time. This approach examines cognitive function dynamics in response to environmental factors, using quantitative measurements and mixed data integration.

The longitudinal design will capture evolving relationships between TC, CO₂ levels and cognitive function over time, facilitating the observation of cumulative impacts and changes in cognitive functioning in response to environmental conditions.

The methodology for this section encompasses several key components:

- **Pilot testing** to refine methods and address potential design issues prior to full-scale implementation.
- **Quasi-experimental design** for controlled manipulation of variables such as temperature and CO₂ levels.
- **Cognitive assessments** using standardized tests (see **Table 4.7**) to evaluate cognitive performance under varied environmental conditions, detailed in Chapter 7.
- **Sensor deployment** for precisely measuring the TC parameters and metabolic CO₂ levels in experimental setups.

- **Repeated measures** involving multiple cognitive assessments to track participant responses to different environmental conditions at various times.
- **Panel study** following three cohorts (S1-1 to S1-3) to monitor changes, with cognitive tests conducted in School 1, as further elaborated in Chapter 7.

Experimental design

The quasi-experimental design is pivotal in evaluating the impact of classroom environmental conditions on cognitive function. Three distinct classroom conditions will be examined:

1. **'Test 1' hypothesis:** Standard classroom conditions, serving as a baseline for typical learning environments.
2. **'Test 2' hypothesis:** The increase in marginal temperature with open windows is expected to have a minimal impact on cognitive performance.
3. **'Test 3' hypothesis:** Closed windows and doors with a heater, altering thermal comfort and CO₂ levels, likely influencing cognitive function.

To optimise student performance based on cognitive fluctuations, tests will be scheduled for both AM and PM sessions, aligning with peak cognitive times observed in the mid to late morning and mid-afternoon, as noted in the study by Jarraya et al.

Operationalising variables

The study manipulated thermal comfort and CO₂ levels to examine their effects on cognitive function. Thermal comfort was adjusted by modifying temperatures in degrees Celsius (°C) while maintaining a standard percentage of RH, and CO₂ levels were altered in parts per million (ppm) by controlling ventilation. Using standardised units ensures consistency in environmental changes.

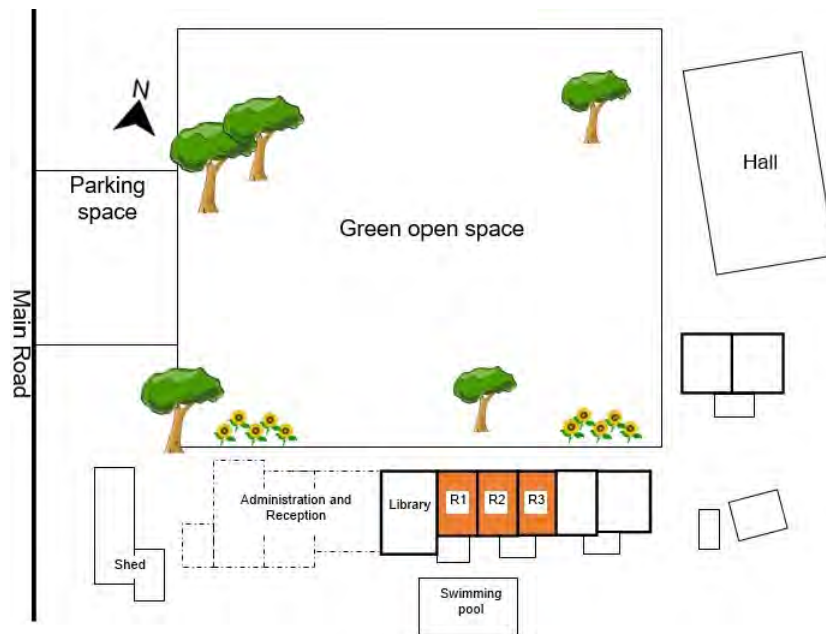
Cognitive abilities were assessed using tasks from an online cognitive test system known for its reliability and validity. These tasks targeted cognitive domains such as concentration, reasoning, and short-term memory. Administering the same tests under all environmental conditions allows for a consistent performance comparison and ensures that the tests measure the intended constructs.

Data collection

Participants - Aim 3

Continuing in School 1 with classrooms in Year 5 and Year 6, including post-mould remediation (**Figure 4.18**), the PI implemented the learning from the pilot study.

FIGURE 4.18: *Site Map of School and Location and Study Classrooms*



Students engaged in cognitive tasks on school laptops through Creyos (“Creyos”, [n.d.](#)), familiarising themselves with gamified tasks (as seen in **Figure 4.19**).

FIGURE 4.19: *Students Undertaking ‘Gamified’ Online Creyos Tests*

The seating choices were left to students (**Figure 4.20**) for an authentic assessment of the impact of the environment on cognitive performance. Three test conditions were used: managed by the teacher (T1), marginally warm (T2), and elevated levels of CO₂ and temperature (T3), to assess various environmental influences.

FIGURE 4.20: *Students Personal Seating Choices during Cognitive Test*

Sample Size

In post-COVID studies, schools used composite classrooms, where students from several consecutive year groups were grouped in one classroom. For this doctoral study, only students from Year 5 and Year 6 (ages 9-11) were directly included. However, Year 4 students were also present in these same classrooms. It is crucial to account for their contribution to metabolic CO₂ levels in the classroom, despite their non-participation in the cognitive aspects of the study.

Table 4.5 summarises the distribution of students by classroom for 2024, reflecting participation restrictions due to ethical guidelines. The table enhances transparency in demographic data, explicitly outlining the participation of Year 5 and Year 6 students in the cognitive tests.

TABLE 4.5: *Number of Students per Classroom by Academic Year for 2024*

	S1-1	S1-2	S1-3
Year 4	n/a	n/a	n/a
Year 5	5	9	11
Year 6	13	14	8
Total No. of Participants	18	23	19

The scheduling matrix (**Table 4.6**) strategically avoids post-lunch assessments, addressing the postprandial dip phenomenon (Monk, 2005; Smith, 1990). The matrix ensures a fair distribution without overlaps by organising three randomly assigned tests over eight weeks in the morning and afternoon sessions. Its visual format effectively communicates the test schedule to students, teachers, and staff.

TABLE 4.6: *Study Design for Cognitive Tests Over Eight Weeks for 2024*

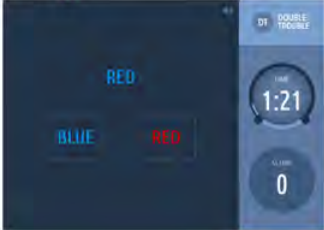
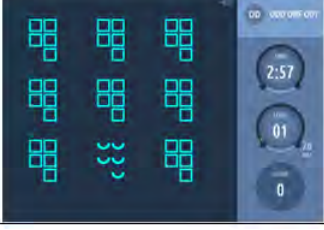
Week	Test 1	Test 2	Test 3
1	S1-3 AM	S1-1 AM	S1-3 PM
2	S1-1 AM	S1-3 PM	S1-3 AM
3	S1-1 PM	S1-2 AM	S1-2 AM
4	S1-2 AM	S1-2 AM	S1-1 PM
5	S1-3 PM	S1-1 PM	S1-3 AM
6	S1-1 AM	S1-2 PM	S1-1 AM
7	S1-2 PM	S1-1 AM	S1-2 AM
8			S1-2 PM

Validity and Reliability

Evaluating the impact of classroom environmental conditions on cognitive function requires robust validation and reliability of measurement methods. Standardised cognitive tests, administered consistently under different environmental conditions, aim to explain the influence of levels of TC and CO₂ on cognitive performance. The study's testing protocol aims to attribute any observed differences in cognitive function directly to intentional environmental manipulations, enhancing the credibility of the result.

Employing an online system (Table 4.7) minimises human error, ensuring the reliability of the measurement. The study improves confidence in the reliability of the observed effects by performing repeated measures under varied but consistently applied conditions.

TABLE 4.7: Four Neurocognitive Tasks from Creyos

Task name	Image	Real-life related activity
Double Trouble		Blocking out background conversations when trying to focus on something
Spatial Planning		Packing items into the trunk of your car so that they all fit
Spatial Span		Following a set of dance moves
Odd One Out		The ability to determine that something is true based on a set of facts

The research focusses on three cognitive domains: concentration, reasoning, and short-term memory, omitting verbal ability tests due to the proportions of the ESOL students. Criteria for test selection and task design included the use of gamified approaches, age appropriateness, distinctiveness to investigate cognitive domains, and sensitivity to detect changes.

Task durations vary, as outlined in **Table 2.15**, with this cognitive test scheduled for 15-20 minutes.

Data analysis

In accordance with ethical constraints, detailed demographic data, including age and gender, will not be collected for the study. The analysis will focus on broader groupings by Year or Cohort. The study analyses data collectively by cohort without specific demographic breakdowns. Each classroom serves as a distinct cohort.

The R programming environment (R Core Team, 2021) will help interpret and present the interactions between cognitive performance and environmental variables.

The six-month field study investigates the impact of TC and CO₂ on concentration, reasoning, and memory in Year 5 and Year 6 students in NZ primary schools. The research aims to suggest interventions to optimise learning environments by performing tests under three different conditions. **This approach considers COVID-19 constraints and natural ventilation systems.**

4.3.6 Statistical tests employed

Normality tests, such as the **Shapiro-Wilk test**, was used to determine whether a data set is well modelled by a normal distribution (Hanusz et al., 2016) and to compute the probability that a random variable underlying the data set is normally distributed (Das and Imon, 2016; Hernandez, 2021). More technically, these tests assess the hypothesis that a sample comes from a normally distributed population.

If the data is found to be normally distributed, parametric tests such as the **Analysis of Variance (ANOVA)** can be used (Henson, 2015). ANOVA assumes that the populations from which sample groups are drawn are normally distributed and have equal variances. The main advantage of ANOVA is that it allows for the comparison

of more than two groups at the same time to determine if at least one sample mean is different from the others (Henson, 2015; Hernandez, 2021).

On the other hand, if data is not normally distributed, non-parametric tests like the **Kruskal-Wallis test** are more appropriate (MacFarland and Yates, 2016). This test does not assume a normal distribution and is used to determine if there are statistically significant differences between three or more groups of independent variables on a continuous or ordinal result (Hecke, 2012; Ostertagova et al., 2014).

In summary, the choice of the **normality test** impacts the subsequent statistical method used. By confirming or rejecting the normality of the data, you can ensure that the assumptions of the subsequent statistical tests are met, which is crucial to obtain valid and reliable results.

Linear regression analyses were conducted to explore the relationship between environmental conditions and cognitive test scores (Kumari and Yadav, 2018). At the same time, ANOVA was used to determine the effects of environmental type and room factors on cognitive performance (Henson, 2015).

To mitigate the influence of numerous external factors on cognitive test results, a within-subjects control approach was adopted. This design allows each participant to serve as their own control, enabling comparisons of individual performance under varying conditions while keeping external variables constant. Data analysis can account for these variables through techniques such as repeated measures ANOVA to assess changes over time, or by incorporating them as covariates in mixed effects models. Including each participant as a random effect allows for the modeling of individual variability independent of treatment or condition effects. In addition, maintaining each participant within the same classroom throughout testing controls for room-specific effects.

Cronbach's alpha, was used to measure the internal consistency reliability of the Teachers window opening questionnaire. The test assesses how closely related a set of questions is as a group, an essential aspect of the scale or test's reliability. Indicates how well the elements of a test measure the same characteristic or construct (Barbera et al., 2020; Cho and Kim, 2015).

4.3.7 Dealing with confounders

Addressing confounding variables in IEQ research in classroom settings impacted by COVID-19 involves identifying and controlling potential factors that could influence the study results. Confounders in IEQ research that focus on levels of TC, RH and CO₂ among primary school students and cognitive functioning include classroom occupancy, external environmental conditions, building design, building age, individual health, adaptive behaviours, and more. These interplaying factors require careful consideration to design and interpret IEQ research effectively.

To mitigate confounding effects, the PI plans to employ a study design involving a randomised controlled crossover approach. This design encompasses three different test conditions: baseline, mild thermal discomfort, and elevated CO₂ and temperature, ensuring systematic comparison while controlling external variables. Additional strategies include environmental monitoring, building evaluations, pilot studies, and transparent data reporting to improve the validity and reliability of the research.

These measures aim to reduce the impact of confounders, providing more accurate insights into how IEQ influences cognitive functioning in school environments.

4.4 Ethics

This study has several ethical applications associated with it. These are available in **Appendix C**.

- Low-risk application as part of Course 218.340.
- Low risk - # 17712 for the Teacher Questionnaire (2nd deployment).
- Low risk - # 21472 Case studies on indoor environment parameters of primary school classrooms in NZ.
- Low risk - # 22115 - Carbon Dioxide Levels and Cognitive Performance: Looking for the relationship through an electroencephalogram in adults.
- High-risk - SQA 2153 for conducting observation studies and cognitive tests in primary schools.

This section delves into ethical aspects of the research framework, including informed consent, confidentiality, data security, and bias mitigation, the protection of research integrity, and the well-being of participants. By consolidating ethical discussions within this chapter, the thesis streamlines content, avoiding redundancy, and enhancing clarity. Each subsection integrates relevant ethical considerations, enriching the analyses with contextual depth.

This structured approach enhances narrative coherence, underlining the PI's commitment to ethical rigour, and strengthening the credibility of results rooted in a solid ethical foundation. Such systematic content arrangement respects the reader's time while demonstrating the commitment to thorough ethical scrutiny throughout the thesis.

Massey University employs an ethical review process to ensure that research aligns with ethical standards, especially with respect to human participants, animals, or sensitive data. The "low-risk" ethics application streamlines review for minimal-risk research, focussing on noninvasive approaches with low potential for harm. Researchers, including PI, submit detailed study applications to the Low-Risk Ethics panel, describing research objectives, data collection methods, consent procedures, and participant protection measures. The panel assesses applications against ethical criteria, expediting approval compared to higher-risk studies, and emphasising researchers' continued ethical responsibilities despite streamlined approval processes.

4.4.1 General ethics

All measures taken in this study ensured participant confidentiality throughout data handling and analysis. Personal identifiers were decoupled from response data and all information was encrypted and securely stored following data protection regulations. Documentation of all data handling and preparation stages provided transparency and reproducibility.

4.4.2 Aim 1 ethical considerations

Following the Massey University Human Ethics review process, the school principals gave their informed consent for participation in the study, collaborating with NZ

MoE during school recruitment.

Installation of IEM and other sensors

Installing IEQ equipment in primary school classrooms involves ethical considerations ensuring occupant safety, well-being, and privacy:

1. **Health and safety:** Priority is given to the safety of children and staff, installing IEQ equipment to minimise risks (Coulby et al., 2023).
2. **Privacy:** Address privacy concerns related to the monitoring capabilities of advanced IEQ systems, ensuring data collection respects privacy (Coulby et al., 2023).
3. **Minimizing disruption:** Scheduling installation, maintenance, and data collection to minimise disruption to educational activities, often during non-instructional hours or breaks.

4.4.3 Aim 2 ethical considerations

Distribution of teachers questionnaires

Collaboration was ensured through permission from previous students and ethical approval from the Ethics Advisor of Massey University, Patsy Broad (**Appendix C**), ensuring research integrity.

Due to the development of the questionnaire occurring before joining the research team, no details about its creation can be provided. Upon joining the research team in 2017, the PI used the same format.

Before data collection, a comprehensive information letter was presented to all participants. This letter detailed the purpose, rationale, duration, and participation expectations of the study. It emphasised the voluntary nature of participation, without monetary compensation or other incentives provided.

The letter also outlined participants' rights, highlighting their freedom to join, continue, or withdraw from the study without repercussions, aligning with ethical guidelines. It ensured complete confidentiality of the collected data, including strict protocols for handling photographs or images and procedures for data

anonymisation and secure storage.

Participants were informed about the study's data-safeguarding measures, the dissemination of results, and the non-identifiable nature of individual responses. Contact details for the research team and ethics oversight body were provided for any concerns or further information.

Informed consent was obtained in written or digital form and emergency plans were in place to address unintended consequences or emotional distress, ensuring the welfare of the participants throughout the investigation.

Observation studies

In a school-based observational study on window-opening behaviour, ethical considerations include

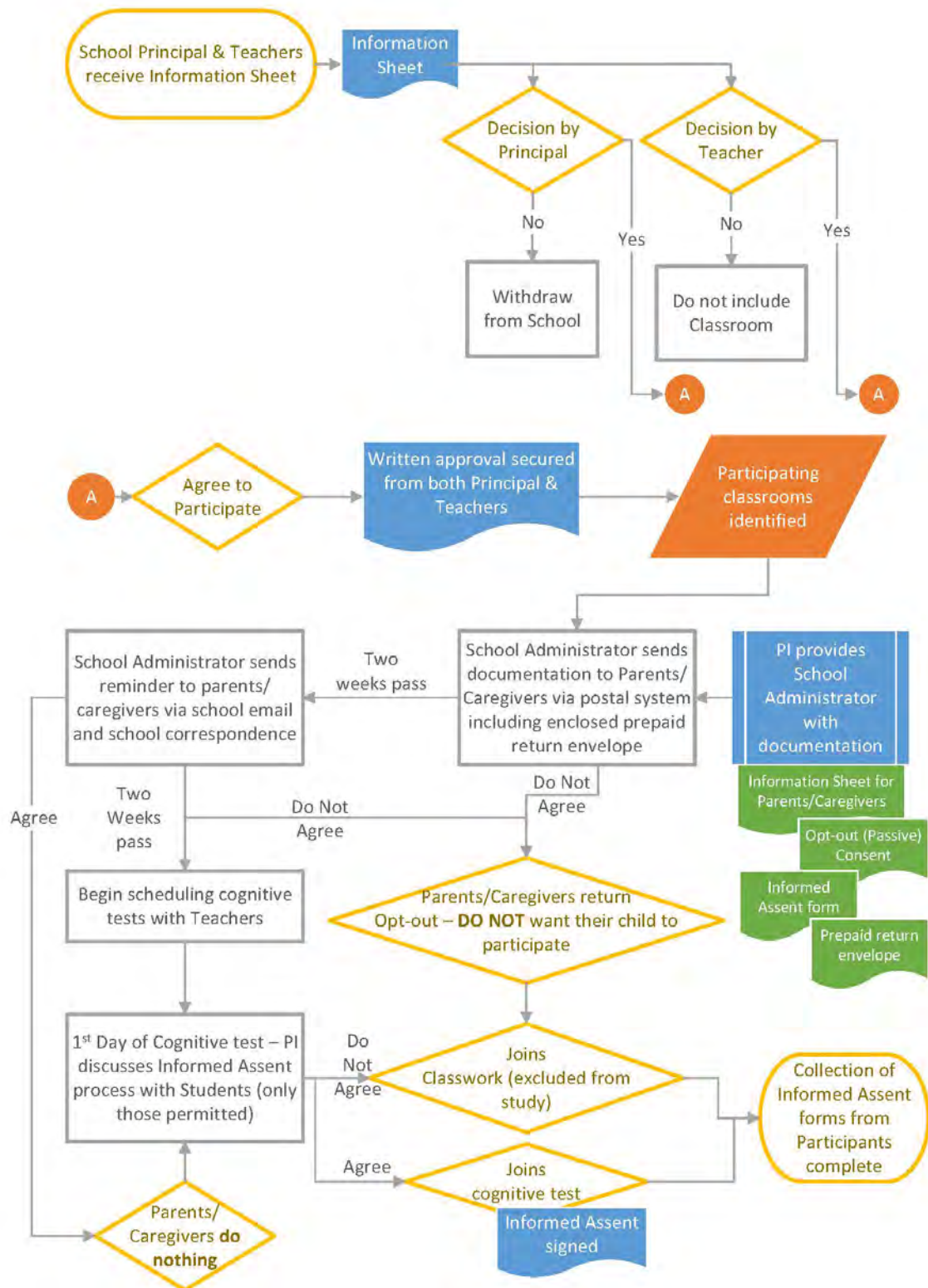
- **Privacy:** Ensure individual privacy by avoiding identifiable images, especially of children, in study-related photography.
- **Minimizing disruption:** Design of the study to minimise disruption to the school environment, using unobtrusive observation methods to maintain normal behaviour and learning.

The installation of door and window sensors adhered to the ethical guidelines previously outlined in Section 4.4.2.

4.4.4 Aim 3 ethical considerations

The research adhered to the Massey University Human Ethics (High Risk) protocols, as detailed in the SOA 21/53 approval document. **Figure 4.21** illustrates the consent acquisition process.

FIGURE 4.21: Summary of Consent/Assent Procedure



The school principal and teachers received information sheets. Upon agreement to participate, written approval was obtained from both the school principal and the participating teaching staff.

Afterwards, information sheets outlining the research and opt-out consent forms were shared with parents and caregivers of the targeted students, including the Year 5 and 6 students. The opt-out process allowed for passive consent, where non-response signified participation agreement. Two weeks after the initial distribution, a reminder was sent via school communication channels to prompt outstanding responses (if any). On assessment day, students without consent forms could participate in the cognitive assessment by signing an informed consent form in the presence of the PI.

The various forms can be viewed in **Appendix C**.

4.5 Pilot study to validate the cognitive test methodology

4.5.1 Introduction to pilot study

The placement of the pilot study within the Methodology chapter, rather than the results and discussion of Chapter 5, reflects its primary function as a validation and refinement of the chosen research methods. The pilot study, while generating preliminary data that was presented at the Healthy Buildings 2019 Asia and Pacific Rim conference in China (**Tookey; 2019**), mainly served to assess the feasibility and effectiveness of the research instruments and procedures chosen.

Specifically, it allowed for the evaluation and subsequent adjustment of (student expectations; improved engagement; reduced misunderstandings; resolution of queries; better performance and iterative comprehension checks). This iterative process, informed by the findings of the pilot study, strengthened the rigour and reliability of the subsequent data collection and analysis applied to the full study. Integrating the pilot study's methodological implications into the Methodology Chapter provides a cohesive and transparent account of the research design evolution. This approach emphasises the pilot's role in justifying and refining the final methodology, rather than presenting preliminary findings as stand-alone research

outcomes. Consequently, this placement strengthens the methodological foundation of the thesis and clarifies the rationale behind the chosen research approach, aligning with the principles of iterative research design as described by (Casula et al., 2021; Gregory, 2011).

4.5.2 Background to pilot study

This pilot study aimed to investigate the impact of different environmental conditions within a primary school setting on cognitive performance among students. The selected primary school, constructed in 1965, is located on the North Shore of Auckland, an area characterised by a temperate climate with an average annual temperature of 15.6 °C and an annual rainfall of 1,231 mm (NIWA, 2023). The school has a population of 160 children aged 5 to 11, distributed in seven classrooms and a library space. The classrooms are designed for cross ventilation and natural airing, with the specific research classes (S1-1 to S1-3) located approximately 90 m from the Main Road, which will minimise noise interference.

The pilot study was conducted in August on S1 and September on S2. The details of the participants is outlined in **Table 4.8**

TABLE 4.8: *Participant Demographics for Pilot Study (August/S1 & September/S2)*

Month	Classroom	Year 4	Year 5	Year 6	Total
Aug	S1	n/a	13	12	25
Sept	S2	n/a	12	5	17
Total number of participants					42

4.5.3 Ethics protocol of pilot study

The study followed the Massey University Human Ethics (High Risk) protocols (approval document SOA 21/53). Written consent was obtained from the school principal and the teaching staff. Information sheets and opt-out consent forms were distributed to parents of Year 5 and 6 students, with a reminder sent two weeks later through school communication. On the day of the test, the participants were asked to give their consent, as illustrated in Figure 4.21.

4.5.4 Methodology of pilot study

Cognitive tests

Students' cognitive performance was assessed using the Creyos platform, previously known as Cambridge Brain Sciences (CBS). This web-based platform includes 12 validated neuropsychological tasks adapted for self-administration over the Internet, including some that focus on audio and speech processing. For this research, the main focus is on assessing concentration, reasoning, and short-term memory. Given the limited time available in field studies, it is not feasible to administer all tests; therefore, a careful selection of the most relevant tasks was necessary.

In choosing which tasks to include, the PI prioritised those that best aligned with the research objectives. In addition, it is important to note that these tasks were originally intended to be tested in conjunction with EEG measurements. As such, the PI selected tasks that could effectively stimulate delta brainwaves.

Tasks automatically adjust their difficulty level based on real-time performance to maintain optimal challenge. Four specific tasks - Double Trouble (DT), Spatial Planning (SP), Spatial Span (SS), and Odd One Out (OOO) — were selected.

Test administration of pilot study

Students received a detailed briefing on the tasks accessed using school-provided laptops. The tests were designed to be completed in 15 to 20 minutes. No seating arrangements were prescribed, allowing students to choose seats based on personal comfort and ensuring a natural setting. As three classrooms participated, each environmental condition was tested.

Environmental conditions of pilot study

One of the three environmental test conditions was used:

1. Test 1: Baseline conditions with standard classroom settings.
2. Test 2: Slightly increased temperature using a heater with open windows.
3. Test 3: Increased temperature using a heater with closed windows and doors.

The levels of CO₂ concentration, ambient temperature and HR for each test condition were recorded as:

- Test 1: CO₂ concentrations around 608 ppm, ambient temperature at 21.4 °C, and RH at 54%.
- Test 2: CO₂ concentrations close to 707 ppm, indoor temperature at 23.3 °C, and RH at 51%.
- Test 3: CO₂ concentrations around 1437 ppm, temperature at 24.2 °C, and RH at 47%.

Data analysis of pilot study

To analyse the data, the Shapiro-Wilk normality test was applied (Hanusz et al., 2016). In cases where normality was confirmed, ANOVA was used to compare continuous variables (Henson, 2015). If normality was not confirmed, the Kruskal-Wallis test was used (MacFarland and Yates, 2016). Linear regression analyses were performed to explore the relationship between environmental conditions and cognitive test scores (Kumari and Yadav, 2018). At the same time, ANOVA was used to determine the effects of environmental type and room factors on cognitive performance.

Shapiro-wilk test results of pilot study

Shapiro-Wilk test results indicate normal distribution for most cognitive tests under three conditions.

4.5.5 Results of pilot study

ANOVA and linear regression analysis

Distinct results among the various cognitive tasks and environmental conditions:

- Test 1: The most conducive to optimal cognitive performance.
- Test 2: Mixed results with marginal impact on performance.
- Test 3: Negative impact on cognitive performance due to elevated CO₂ levels and increased temperature, especially noticeable in S1-R3.

4.5.6 Discussion of pilot study

The preliminary results suggest that moderate environmental conditions (Test 1) support better cognitive performance among primary school students. Elevated CO₂ levels and higher temperatures (Test 3) appear to alter cognitive functioning, specifically affecting tasks related to attention and memory. These findings underscore the importance of maintaining optimal classroom conditions to improve academic performance and cognitive functions.

4.5.7 Conclusions and validation of pilot study

The study highlights the influence of environmental factors such as CO₂ levels, temperature, and humidity on cognitive performance. The test results varied according to the specific room and environmental conditions, indicating that even small changes can have measurable effects. Future research should consider the comprehensive impact of classroom settings, student characteristics, and instructional methods to effectively optimise educational environments. Moderation in environmental parameters tends to support cognitive performance, whereas extremes can be detrimental.

4.5.8 Learning from pilot study

When introducing students to the online cognitive test, it was observed that providing them with screenshots and spending more time on the initial briefing was more effective than simply talking to them and then allowing them to proceed directly to the tutorials. The observed behaviour indicated that students were more eager to begin the 'test' without fully understanding the necessary steps or objectives.

Several key factors highlight the significance of this aspect when establishing any internet-based endeavour:

1. **Enhanced visual understanding:** Screenshots provide a visual representation of what students can expect, reducing the ambiguity and anxiety associated with unknown elements (Raiyn, 2016).
2. **Improved engagement:** Detailed briefings can clarify instructions, helping students focus more on tasks and their objectives rather than deciding what to do next (Burn et al., 2022).

3. **Reduced misunderstandings:** A comprehensive initial briefing ensures that key instructions are understood uniformly in all students, reducing the need for repeated explanations and interruptions (Raiyn, 2016).
4. **Immediate resolution of queries:** Spending more time in advance allows students to ask questions and clarify doubts before starting, leading to a smoother testing process (Wasik and Hindman, 2018).
5. **Better performance:** When students understand the tasks better, they can perform them more effectively, leading to more accurate assessment results (de Vries et al., 2022; Heitink et al., 2016).
6. **Iterative comprehension check:** Following the initial briefing, employ a series of targeted questions to verify students' grasp of the tasks. When there are intervals between cognitive evaluations, it is crucial to reiterate the instructions at the beginning of each session. This repetition, significant during extended breaks, helps reinforce understanding and ensures consistent execution of tasks (Honeybourne, 2018; Ker and van Gorp, 2023).

By implementing these strategies, the transition from introduction to execution will be smoother, thus enhancing the overall effectiveness of cognitive assessments and learning activities.

4.6 Prelude to results and discussion chapters

The next chapters present the core research objectives of this thesis, progressively improving the understanding of TC&V in primary school classrooms and its impact on cognitive performance.

Chapter 5 establishes the baseline IEQ conditions in primary school classrooms, providing a detailed analysis of the environmental factors within these settings and setting the foundation for subsequent investigations.

Chapter 6 explores teachers' airing behaviours and their influence on the classroom environment, intertwined with Chapter 5's results. This symbiotic relationship reveals the dynamic nature of classroom conditions.

Building on Chapters 5 and 6, Chapter 7 examines how specific environmental conditions affect cognitive performance in primary schools. These conditions include a teacher-managed natural ventilation scenario, slightly elevated warmth, and elevated CO₂ levels with elevated temperatures, which incorporate COVID-19 safety measures.

Each chapter includes a dedicated discussion section that merges research outcomes with pertinent literature to offer in-depth analysis and interpretation.

This coherent structure across the chapters facilitates a comprehensive exploration of the research objectives, weaving together IEQ and cognitive performance aspects in primary school classrooms.

Following the results and discussions, Chapter 8 will synthesise key findings and propose recommendations, emphasising practical implications and guiding future research and policy directions.

Chapter 5

THERMAL COMFORT and CO₂ LEVELS IN NZ CLASSROOMS

5.1 Introduction

This chapter outlines the results of the TC and ventilation (TC&V) data collected from primary schools in four NZ regions. CO₂ levels have been used as a proxy for ventilation adequacy in indoor spaces. The data covered periods before and after the onset of the COVID-19 pandemic. In the following sections, the PI will discuss the findings. The insights from this data will serve as a foundational benchmark, informing the two results chapters.

In this section, the PI will present an analysis of the data collected during the deployment of IEMs. All results discussed here are based on data collected within the **operational timeframes** of NZ schools, **specifically Monday through Friday from 09:00 to 15:00**, excluding school holidays. This period is aligned with the typical school day, ensuring that the environmental conditions monitored reflect the actual classroom environments where students and teachers engage in daily activities.

All results are reported against the regulatory documents outlined in **Section 2.5**.

In this study section, steady-state CO₂ levels have been used consistently. Subsequently, data analysis was performed to determine the mean and standard deviation.

The classrooms in this study are not airtight - primarily due to the presence of louvre windows on the north facing side of the classrooms. This was outlined

on several occasions in Chapter 4 and will be discussed again in Chapter 6. The only classroom that is airtight is Classroom C, examined in Auckland 2017. All classrooms are naturally ventilated (NV).

Standard classroom occupant densities range from 1.8 to 2.4 m² per person. A new Ministry of Education (MoE) policy will reduce the average class size for years four to eight in primary schools from 29 to 28 students per teacher by 2025 (Ministry of Education, 2023; RNZ National, 2023).

5.2 Auckland - 11/8/2017 to 6/12/2017 (pre COVID-19)

This deployment presented an unusual situation where my role as the PI did not extend to personally conducting the data analysis. Unfortunately, obtaining the raw data was not feasible, marking a significant deviation from the customary research process. This unexpected challenge necessitated the reliance on the written analysis conducted by the research team. It is important to note that I was actively involved as a research assistant during this deployment (predoctoral study), contributing to the data collection and preliminary analysis phases.

Based on the research findings, the current analysis has undergone rigorous scrutiny to ensure its validity. The implications of using secondary data analysis have been addressed within the limitations of the study and considered when formulating the interpretations and conclusions of this research.

IEMs were located in one North Shore Auckland primary school. Monitoring occurred in three classrooms during one winter week and one early spring week in 2017. The results are outlined in Table 5.1.

TABLE 5.1: Summary of Auckland Monitored Classrooms

	Class A	Class B	Class C
Notes:	A faulty window caused a draught.		Newly constructed classroom with high thermal resistance.
CO₂	Levels consistently below 1000 ppm due to better ventilation and fewer occupants.	Exceeding 1000 ppm for 66% of school hours and 1500 ppm for 40% of the school day.	
Temp	Overheating issues in spring with temperatures >24 °C.	Overheating in spring with temperatures >26 °C for half of the day.	Overheating in spring with temperatures >24 °C.

In class A, two SKOMOBO IEMs were placed side by side for quality assurance. The measurements of the two units were identical, indicating consistency between the IEMs.

5.3 Hawke's Bay, Christchurch, and Dunedin - 9/9/2017 to 28/10/2018 (pre COVID-19)

The next deployment occurred in three areas (Hawkes Bay, Christchurch, and Dunedin) and covered all four seasons from 9th September 2017 to 28th September 2018.

To manage the extensive dataset acquired during deployment, the analysis in this section focusses on four representative weeks per season, specifically school week periods (Monday 09:00 to Friday 15:00). These weeks, detailed in Appendix D Table D.1, effectively captures seasonal trends and patterns. Data presented here excludes weekends and school holidays.

5.3.1 Meteorological reporting: Outside compartment

Table 5.2 presents the mean and standard deviation (SD) of four climate variables: ambient temperature (Temp), relative humidity (RH), wind speed (Wind) and rainfall (rain) in spring, summer, autumn and winter for three cities in NZ: Hawke's Bay, Christchurch, and Dunedin based on the schedule in D.1. All meteorological data had been sourced from CLiFlow (National Institute of Water and Atmospheric Research, 2022).

TABLE 5.2: *Seasonal Climate Data Comparison for New Zealand Cities*

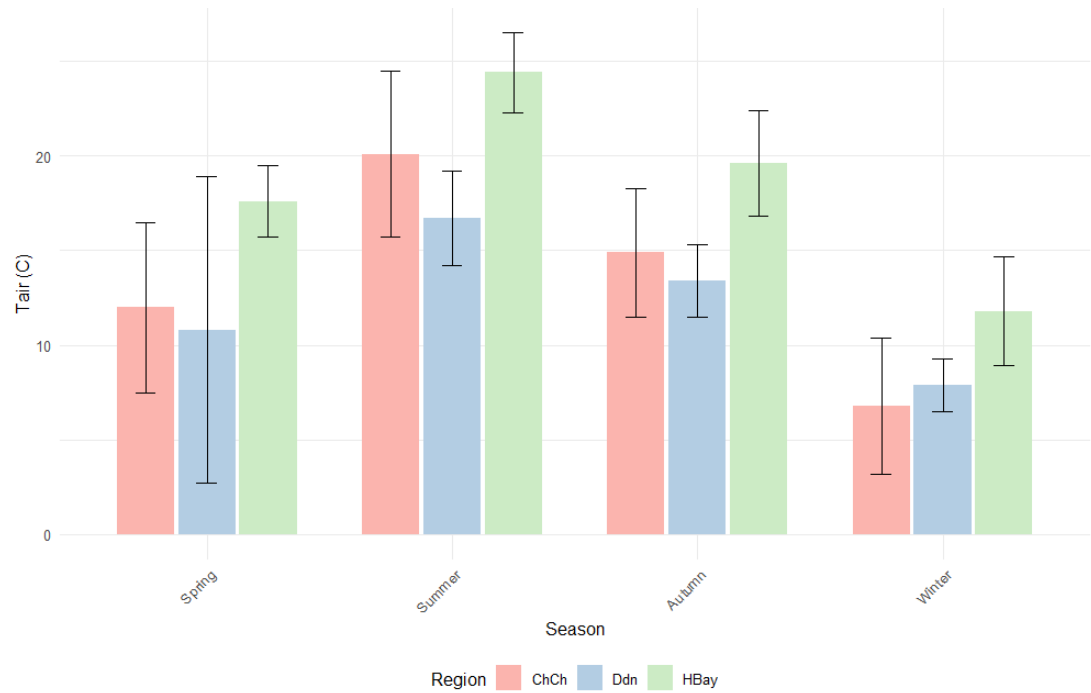
Season	Region	Tair(C)	RH(%)	Rain (mm)	Windspeed (M/Sec)
Spring	ChCh	12.0 [4.5]	64 [17]	5.3 [5.3]	2.7 [0.3]
	Dunedin	10.8 [8.1]	63 [14]	39.7 [14.7]	3.3 [0.3]
	Hbay	17.6 [1.9]	69 [7]	11.1 [1.7]	3.3 [0.6]
Summer	ChCh	20.1 [4.4]	71 [22]	5.3 [5.3]	2.7 [0.3]
	Dunedin	16.7 [2.5]	76 [12]	48.9 [10.3]	3.05 [0.4]
	Hbay	24.4 [2.1]	73 [9]	66.6 [10.0]	2.9 [0.7]
Autumn	ChCh	14.9 [3.4]	82 [14]	8.8 [8.8]	2.55 [0.4]
	Dunedin	13.4 [1.9]	76 [10]	46.5 [0.7]	3 [0.3]
	Hbay	19.6 [2.8]	75 [13]	95.3 [15.2]	2.8 [0.5]
Winter	ChCh	6.8 [3.6]	84 [12]	29.6 [4.6]	2.25 [0.4]
	Dunedin	7.9 [1.4]	77 [7]	120 [74.2]	3.1 [0.7]
	Hbay	11.8 [2.9]	82 [9]	117.5 [13.9]	3.0 [0.6]

The data in **Table 5.2** reveals distinct patterns and variations between cities and seasons.

Temperature

Figure 5.1 illustrates the temperature conditions in the three study regions.

FIGURE 5.1: Seasonal Variation of Air Temperature Across Different Cities



The air temperature conditions in three regions, Christchurch, Dunedin, and Hawke’s Bay, demonstrate distinct seasonal variations. During spring, Christchurch experiences an average temperature of 12.0 °C [4.5], while Dunedin is slightly cooler at 10.8 °C [8.1]. Hawke’s Bay, on the other hand, has a milder spring with an average temperature of 17.6 °C [1.9].

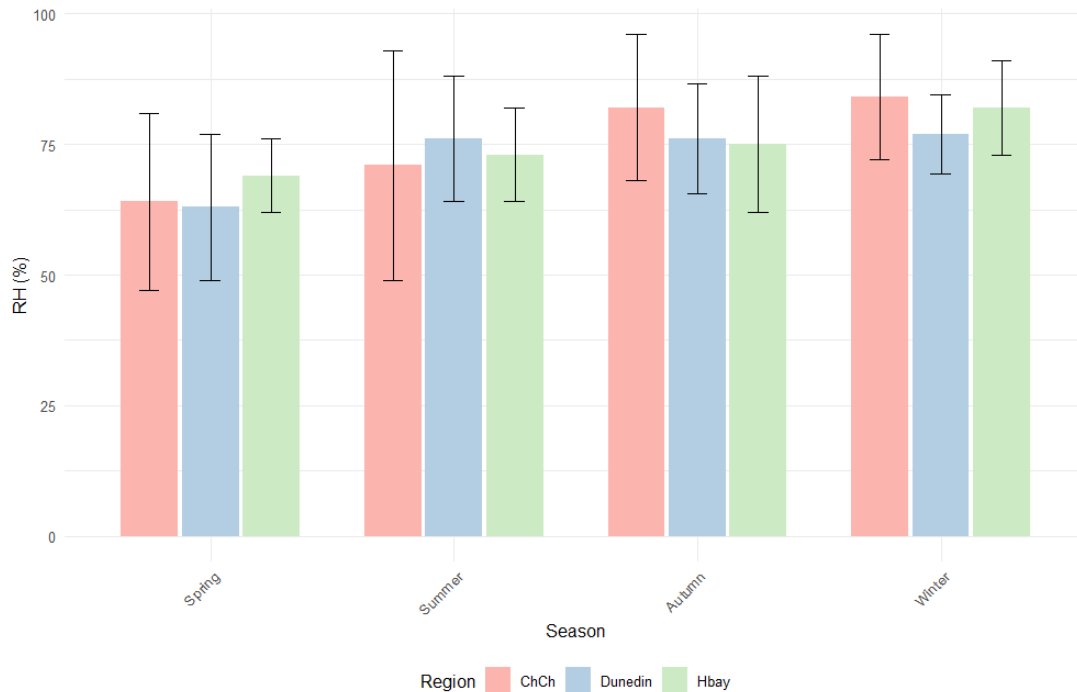
In summer, temperatures rise across all regions, with Christchurch reaching 20.1 °C [4.4], Dunedin at 16.7 °C [2.5], and Hawke’s Bay peaking at 24.4 °C [2.1]. Autumn sees a moderate drop in temperatures, with Christchurch at 14.9 °C [3.4], Dunedin at 13.4 °C [1.9], and Hawke’s Bay at 19.6 °C [2.8].

Winter brings the lowest temperatures, evident in Christchurch’s average of 6.8 °C [3.6] and Dunedin’s slightly higher 7.9 °C [1.4]. Hawke’s Bay again exhibits a more moderate climate, with winter temperatures averaging 11.8 °C [2.9]. These variations highlight the diverse climatic conditions experienced by these regions throughout the year.

Relative humidity

Figure 5.2 illustrates the RH conditions in the three study regions.

FIGURE 5.2: *Seasonal Variation of Relative Humidity Across Different Cities*



The RH conditions in the Christchurch, Dunedin, and Hawke's Bay regions show notable seasonal variability. In spring, Christchurch has an average RH of 64% [17%], while Dunedin's RH is 63% [14%]. Hawke's Bay exhibits a higher and more consistent humidity of 69% [7%].

During the summer, Christchurch experiences an increase in humidity at 71% [22%], indicating greater variability. Dunedin shows a further increase to 76% [12%], and Hawke's Bay records an RH of 73% [9%].

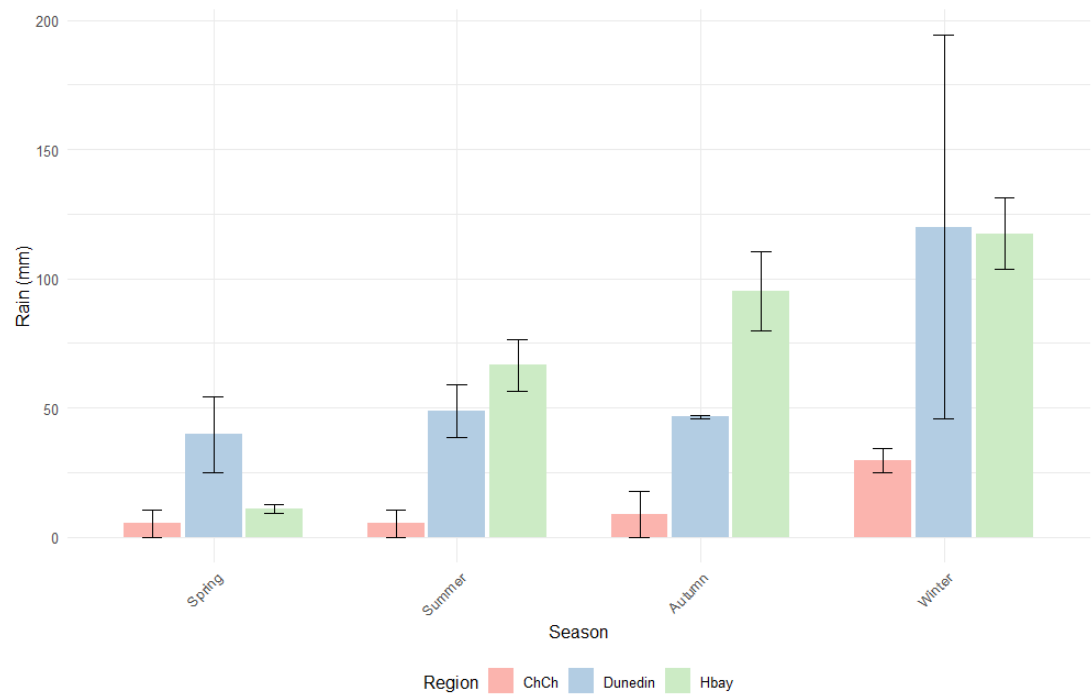
Autumn brings further changes, with Christchurch's RH rising to 82% [14%], Dunedin maintaining a high RH of 76% [10.5%], and Hawke's Bay at 75% [13%]. The winter season sees Christchurch reaching its peak RH of 84% [12%], while Dunedin's RH is 77% [7.6%]. Hawke's Bay remains humid, with an RH of 82% [9%].

These observations highlight the seasonal trends in relative humidity, with each region displaying distinct patterns of variability throughout the year.

Rainfall

Figure 5.3 illustrates the rainfall conditions in the three study regions.

FIGURE 5.3: Seasonal Variation of Rainfall Across Different Cities



The rainfall conditions across the Christchurch, Dunedin, and Hawke’s Bay regions exhibit significant seasonal disparities. In spring, Christchurch experiences an average rainfall of 5.3 mm with a standard deviation equal to the mean, indicating high variability. Dunedin receives significantly more rainfall at 39.7 mm [14.7 mm], while Hawke’s Bay records 11.1 mm [1.7 mm].

Christchurch maintains a similar rainfall pattern during summer with 5.3 mm [5.3 mm]. Dunedin sees an increase to 48.9 mm [10.3 mm], and Hawke’s Bay experiences the highest summer rainfall at 66.6 mm [10.0 mm].

Autumn slightly increases Christchurch’s rainfall to 8.8 mm [8.8 mm]. Dunedin’s rainfall is 46.5 mm with a minimal variability of 0.7 mm, and Hawke’s Bay observes a significant rise to 95.3 mm [15.2 mm].

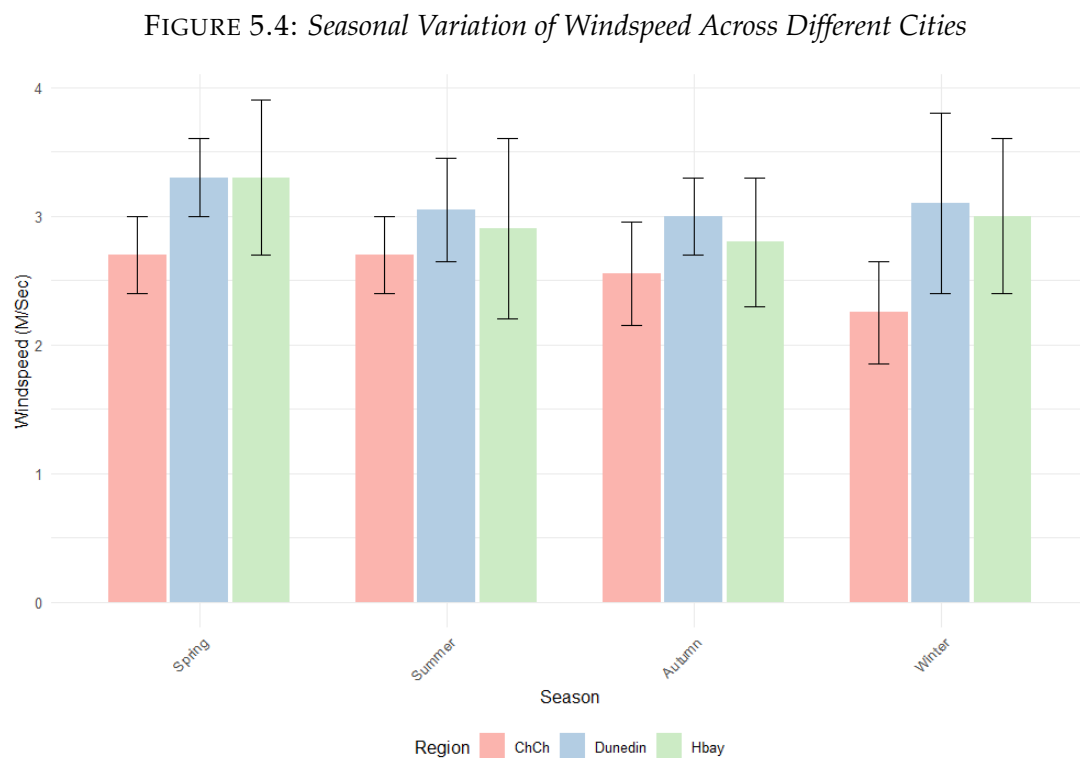
Winter shows the most dramatic changes, with Christchurch receiving 29.6 mm of rainfall (SD = 4.6 mm). Dunedin experiences a substantial increase to 120 mm, albeit

with high variability (SD = 74.2 mm). Hawke’s Bay also experiences high rainfall in winter, with 117.5 mm and a standard deviation of 13.9 mm.

These observations highlight the diverse rainfall patterns across the regions, with each season presenting distinct precipitation characteristics.

Windspeed

Figure 5.4 illustrates the windspeed conditions across the three study regions.



The windspeed conditions across Christchurch, Dunedin, and Hawke’s Bay regions show notable seasonal variations. In the spring season, Christchurch experiences an average windspeed of 2.7 m/s [0.3]. Both Dunedin and Hawke’s Bay have a higher average windspeed of 3.3 m/s, with Dunedin showing less variability [0.3] compared to Hawke’s Bay [0.6].

During the summer, Christchurch maintains its windspeed at 2.7 m/s [0.3], while Dunedin sees a slight decrease to 3.05 m/s [0.4]. Hawke’s Bay also experiences a reduction in windspeed to 2.9 m/s, with a higher standard deviation of 0.7.

Autumn slightly decreases Christchurch's windspeed to 2.55 m/s [0.4]. Dunedin's windspeed remains relatively stable at 3.0 m/s [0.3], and Hawke's Bay records a windspeed of 2.8 m/s [0.5].

Christchurch experiences the lowest windspeed in winter at 2.25 m/s [0.4], while Dunedin's windspeed increases to 3.1 m/s with a higher variability [0.7]. Hawke's Bay maintains a consistent windspeed of 3.0 m/s, with a standard deviation of 0.6.

These observations highlight the distinct patterns of windspeed across different seasons and regions, with each location exhibiting unique wind characteristics throughout the year.

In summary, based on the provided climate data for Christchurch, Dunedin, and Hawke's Bay, the climates of these regions differ significantly, which can have substantial impacts on indoor environment quality in classrooms. Hawke's Bay boasts the mildest climate with the highest average temperatures across all seasons, while Christchurch experiences moderate temperatures with colder winters than Dunedin. Dunedin, on the other hand, has the coldest summers but slightly warmer winters compared to Christchurch. These temperature variations would affect classroom heating and cooling requirements, with Hawke's Bay needing less heating in winter and more cooling in summer. At the same time, Christchurch and Dunedin would require significant heating in winter, and Dunedin would require less cooling in summer.

Relative humidity is high in all regions, particularly in winter, with Christchurch experiencing the highest winter humidity at 84%. Hawke's Bay maintains the most consistent humidity levels throughout the year. These high humidity levels could lead to mould growth and classroom discomfort, necessitating dehumidification, especially in Christchurch during winter. Rainfall patterns also vary, with Dunedin receiving the highest overall rainfall, particularly in winter, while Hawke's Bay experiences high rainfall in autumn and winter. Christchurch has the lowest overall rainfall but sees a significant increase during winter. Higher rainfall could increase indoor humidity and potential water ingress issues, especially in Dunedin and Hawke's Bay classrooms.

Windspeed variations are also notable, with Dunedin consistently experiencing the highest windspeeds, Christchurch the lowest (especially in winter), and Hawke's Bay moderate windspeeds with higher variability. These differences in windspeed could impact NV strategies and potentially cause drafts, particularly in Dunedin classrooms.

Considering overall comfort and ease of maintaining indoor environmental quality, Hawke's Bay could be considered the "better" climate. It offers milder temperatures year-round, requiring less extreme heating or cooling, more consistent humidity levels that might be easier to manage, and moderate windspeeds that could facilitate NV without excessive drafts. However, its high rainfall in autumn and winter could pose challenges for moisture control. Christchurch and Dunedin have advantages and disadvantages, with Christchurch having lower rainfall but colder winters and high winter humidity, and Dunedin experiencing cooler summers but higher rainfall and windspeeds, which could complicate indoor environment management. Ultimately, determining the "better" climate would depend on the specific design strategies used in the classroom and the priorities for indoor environmental quality.

5.3.2 Indoor environmental monitoring report: Inside compartment

Missing data

The absence of data (**Table 5.6 to 5.22**) indicates that it was not sent to the Massey University server. Hawke's Bay had 15% missing data, Christchurch had 21% missing, and Dunedin had 7.1% missing. Ensured reliability of data transmission was a focus of future research and development efforts.

Colour code for tables

Tables are colour-coded following Table 5.3.

TABLE 5.3: Colour Coding of Tables According to Regulatory Documents

Colour code and regulatory discussion
Below 16 [16-18[[18-24[[24-28[Above 28 The WHO recommends maintaining a temperature range of 18 °C to 24 °C during school hours when the classrooms are occupied (World Health Organization et al., 1987).
Below 40 [40-60[[60-70[Above 70 According to ASHRAE, the ideal RH should be between 40% and 60% if the temperature is set within the 18 °C to 24 °C range (ASHRAE, 2020).
[400-800[[800-1000[[1000-1500[[1500-2000[[2000-3000[[3000-5000] G4, the NZ Standard for Ventilation and Air Quality (Standards New Zealand, 1990b): This standard suggests that CO₂ levels in indoor environments should stay below 1000 ppm to ensure acceptable air quality. The NZ MoE’s 2017 DQLS also emphasises managing IAQ and TC in classrooms. These guidelines state that CO₂ levels should not exceed 1500 ppm, with a daily average requirement of 1200 ppm or lower to protect the health and comfort of the occupants (Ministry of Education, 2017).
Below 800 [800-1250[[1250-2000[Over 2000 Post-COVID there is a stronger focus on maintaining CO₂ levels well below the 1000 ppm threshold to ensure better ventilation and air quality (Fullbrook et al., 2022).

The green (Table 5.3) indicates exposure within the recommended ranges (Section 2.5). The yellow /orange colour shows exposure slightly outside the recommended range. Red indicates an exceedance beyond the range that children should not be exposed to in a healthy learning environment. These IEM results will be compared with the regulatory documents established in Section 2.5.

IEM reporting in Hawke's Bay schools

The average weekly indoor temperature, RH, and CO₂ levels during school hours (Monday 09:00 to Friday 15:00) for two schools in Hawke's Bay (H1 and H2), please refer to **Table F.1**.

H2-2(A and B) is the classroom in Hawke's Bay where two IEMs are installed. These devices consistently show the same results, confirming the IEM's robustness.

Temperature

Table 5.4 details the percentage of time classrooms in two Hawke's Bay schools conform to different temperature ranges over various seasons.

TABLE 5.4: *Temperature Cuts in Hawke's Bay Schools (09:00 - 15:00 School Days Only)*

School	Room	Season	Below 16	[16-18[	[18-24[	[24-28[	Above 28
H1	1	Spring			73%	27%	
		Summer	na	na	na	na	na
		Autumn			49%	51%	
		Winter	na	na	na	na	na
H1	2	Spring			80%	20%	
		Summer	na	na	na	na	na
		Autumn			100%		
		Winter	34%	21%	45%		
H2	1	Spring			100%		
		Summer			64%	36%	
		Autumn			86%	14%	
		Winter	9%	14%	77%		
H2	2A	Spring			77%	23%	
		Summer			47%	53%	
		Autumn			87%	13%	
		Winter		20%	74%	6%	
H2	2B	Spring			82%	18%	
		Summer			42%	58%	
		Autumn			88%	12%	
		Winter		20%	75%	5%	

Table 5.4 highlights that only one classroom in spring (H2-1) and autumn (H1-2) met the WHO recommended temperature range (18-24 °C) during occupied hours. However, notable exceptions exist: H1-1 and H2-2 often experience temperatures outside this comfort zone, especially in winter for H1-2. These periods may require attention to improve TC, particularly during cold winter months when temperatures can drop below 16 °C, potentially causing discomfort. Furthermore, H1-1 in the autumn and H2-2B in the summer show significant periods with temperatures rising above 24 °C, indicating the need to cool in the summer and potential energy savings opportunities in winter.

Relative humidity

Table 5.5 outlines the percentage of time classrooms in two Hawke's Bay schools maintain RH levels in different seasons.

TABLE 5.5: RH Cuts in Hawke's Bay Schools (09:00 - 15:00 School Days Only)

School	Room	Season	Below 40	[40-60[	[60-70[	Above 70
H1	1	Spring		99%	1%	
		Summer	na	na	na	na
		Autumn		89%	11%	
		Winter	na	na	na	na
H1	2	Spring		100%		
		Summer	na	na	na	na
		Autumn		72%	16%	12%
		Winter		3%	78%	19%
H2	1	Spring		86%	14%	
		Summer		43%	26%	31%
		Autumn		11%	86%	3%
		Winter		79%	21%	
H2	2A	Spring		82%	18%	
		Summer		39%	41%	20%
		Autumn		22%	78%	
		Winter		60%	40%	
H2	2B	Spring		81%	19%	
		Summer		43%	37%	20%
		Autumn		22%	78%	
		Winter		62%	38%	

Based on the provided data (**Table 5.5**), seasonal variations significantly impact the performance of classrooms in Schools H1 and H2.

In School H1, H1-2 generally performs better overall. In spring, H1-2 achieves a perfect 100% within the ideal range, slightly exceeding H1-1's 99%. During the autumn, although H1-2 has a lower percentage within the ideal range (72% vs. 89% for H1-1), it still maintains a fairly high percentage. Furthermore, in winter, H1-2 maintains a respectable 78% within the ideal range.

School H2-1 maintains ideal humidity levels, particularly in spring and autumn. In spring, H2-1 leads with 86%, outperforming H2-2A (82%) and H2-2B (81%). All rooms perform similarly during summer, but H2-1 and H2-2B are better at avoiding high humidity (above 70%). In autumn, H2-1 again leads with 86%, compared to 78% for both H2-2A and H2-2B. However, in winter, H2-2A stands out with the best performance at 40%, followed by H2-2B at 38%, while H2-1 falls behind at 21%. In general, H2-1 demonstrates stronger performance in more seasons, particularly in spring and autumn, while H2-2A excels in winter.

Based on the provided data, spring is the best season for maintaining ideal humidity levels across both schools. In contrast, winter presents challenges, particularly for H2-1, which falls behind at 21%.

Carbon dioxide

Table 5.6 provides valuable information about the two Hawke's Bay classrooms as they relate to metabolic CO₂ concentrations:

TABLE 5.6: CO₂ Cuts in Hawke's Bay Schools (09:00 - 15:00 School Days Only)

School	Room	Season	[400-800[	[800-1000[	[1000-1500[	[1500-2000[	[2000-3000[	[3000-5000[
H1	1	Spring	46%	23%	31%			
		Summer	na	na	na	na	na	na
		Autumn	31%	52%	8%	3%	6%	
		Winter	na	na	na	na	na	na
H1	2	Spring	37%	33%	9%	13%	5%	3%
		Summer	na	na	na	na	na	na
		Autumn	16%	6%	20%	32%	23%	3%
		Winter	38%	4%	22%	18%	17%	1%
H2	1	Spring	72%	15%	13%			
		Summer	9%	22%	30%	21%	18%	
		Autumn	28%	20%	26%	10%	16%	
		Winter	24%	3%	17%	22%	32%	2%
H2	2A	Spring	20%	20%	29%	18%	13%	
		Summer		9%	25%	28%	24%	14%
		Autumn	16%	20%	33%	16%	15%	
		Winter	24%	14%	18%	19%	25%	
H2	2B	Spring	32%	17%	27%	14%	10%	
		Summer		9%	24%	28%	24%	15%
		Autumn	16%	20%	33%	16%	15%	
		Winter	23%	14%	18%	18%	27%	

Comparative analysis reveals that H1 Room 1 performs better in maintaining ideal air quality during spring and autumn, while H1 Room 2 excels in winter. In spring, H1 Room 1 maintains an ideal CO₂ range ([400-800[) for 46% of the time, compared to H1 Room 2's 37%. During the autumn, H1 room 1 continues to lead with 31% of time within the ideal range, surpassing H1 room 2's 16%. However, in winter, H1 Room 2 performs better, achieving 38% within the ideal range. Consequently, considering the higher percentages within the ideal range in multiple seasons, it can be concluded that H1 Room 1 performs better overall to maintain ideal air quality.

The same format will be used to present the results of Christchurch and Dunedin schools.

IEM reporting in Christchurch schools

The average weekly temperature, RH, and CO₂ levels during school hours (Monday 09:00 to Friday 15:00) for four schools in Christchurch (C1, C2, C3 and C4), can be found in **Appendix F.2**.

Classroom C4-3(A and B) is the classroom in Christchurch where two IEMs are installed. These devices consistently show the same results, confirming the IEM's robustness.

Temperature

Tables 5.7 and **5.8** detail the percentage of time the temperature in various classrooms and schools fell within specific temperature ranges throughout different seasons.

TABLE 5.7: Temperature Cuts in Christchurch Schools (Part 1) (09:00 - 15:00 School Days Only)

School	Room	Season	Below 16	[16-18[	[18-24[	[24-28[	Above 28
C1	1	Spring			100%		
		Summer			82%	18%	
		Autumn			100%		
		Winter			96%	4%	
C1	2	Spring	na	na	na	na	na
		Summer			46%	54%	
		Autumn	na	na	na	na	na
		Winter			97%	3%	
C1	5	Spring		3%	93%	4%	
		Summer	na	na	na	na	na
		Autumn			100%		
		Winter			100%		
C2	1	Spring		3%	78%	20%	
		Summer			48%	52%	
		Autumn	na	na	na	na	na
		Winter	na	na	na	na	na
C2	2	Spring		1%	72%	27%	
		Summer	na	na	na	na	na
		Autumn	na	na	na	na	na
		Winter	100%				
C2	3	Spring		5%	95%		
		Summer	na	na	na	na	na
		Autumn	na	na	na	na	na
		Winter	na	na	na	na	na

Based on the data (Table 5.7), C1-1 performs consistently well across all seasons, especially excelling with 100% within the ideal range [18-24[during both spring and autumn, and maintaining high percentages in summer (82%) and winter (96%). C1-2 shows varied performance, achieving 46% within the ideal range [18-24[during summer and 97% during winter. C1-5 excels in winter and autumn with 100% within the ideal range [18-24[, but has significantly lower performance during spring (4%).

Comparatively, C1-1 demonstrates the best overall performance, maintaining the ideal temperature [18-24[range across more seasons and with higher percentages. Specifically, in spring, C1-1 achieves 100% compared to C1-5's 4%. In summer, C1-1's

82% outperforms C1-2's 46%. In autumn, C1-1 matches C1-5's 100%. In winter, while C1-2 slightly edges out C1-1 (97% vs 96%), C1-1's consistency across more seasons favours its overall performance.

Thus, C1-1 performs better overall due to its higher and more consistent performance in maintaining ideal air quality across multiple seasons.

Based on the data (**Table 5.8**), C2-3 performs the best overall, particularly excelling in spring by maintaining the ideal temperature range [18-24[for 95% of the time. C2-1 shows decent performance in both spring and summer, maintaining the ideal range for 78% and 48% of the time, respectively. However, C2-2 struggles significantly in winter, maintaining temperatures below 16 °C 100 of the time, which undermines its overall performance despite reasonable spring performance.

C2-2 was empty for the duration of the study.

TABLE 5.8: Temperature Cuts in Christchurch Schools (Part 2) (09:00 - 15:00 School Days Only)

School	Room	Season	Below 16	[16-18[	[18-24[	[24-28[	Above 28
C3	2	Spring			100%		
		Summer			16%	84%	
		Autumn			100%		
		Winter			99%	1%	
C3	3	Spring		1%	93%	6%	
		Summer			50%	50%	
		Autumn					
		Winter	3%	33%	64%		
C3	4	Spring		2%	81%	17%	
		Summer			6%	94%	
		Autumn			100%		
		Winter		1%	99%		
C4	1	Spring	2%	14%	80%	4%	
		Summer			20%	62%	18%
		Autumn			100%		
		Winter		1%	92%	7%	
C4	2	Spring	13%	33%	50%	4%	
		Summer			38%	62%	
		Autumn			100%		
		Winter	100%				
C4	3A	Spring			100%		
		Summer			8%	82%	10%
		Autumn			100%		
		Winter			66%	34%	
C4	3B	Spring			98%	2%	
		Summer			3%	70%	27%
		Autumn			100%		
		Winter			45%	55%	

Based on the data (Table 5.8), C3-2 demonstrates the best overall performance across multiple seasons. It maintains the ideal temperature range [18-24[100% in spring and autumn and shows high performance in winter 99% and reasonable performance in summer 16%, with the majority at [24-28[, 84%). This consistent performance makes C3-2 the best-performing classroom overall, as it excels in maintaining the ideal temperature range [18-24[across different seasons.

Therefore, based on the data provided (Table 5.8), C4-1 is the most consistently

high-performing classroom across all seasons. Its ability to maintain a comfortable range of temperatures throughout the year makes it the best choice for fostering a stable and productive educational setting.

From the data presented (**Tables 5.7 and 5.8**), it is clear that performance varies across seasons for different classrooms. However, to determine which season is the "best" overall, we must consider the performance across all classrooms.

Spring seems to be a strong season for many classrooms. C1-1 achieves 100% in the ideal range, C2-3 performs best with 95% in the ideal range, and C3-2 maintains 100% in the ideal range. autumn also shows good performance, with C1-1 and C1-5 achieving 100% in the ideal range and C3-2 maintaining 100% in the ideal range.

Winter shows mixed results. C1-2 and C1-5 perform well (97% and 100%, respectively), while C2-2 struggles significantly. C3-2 shows high performance (99%) in this season. Summer generally shows lower performance compared to other seasons, with some exceptions.

Given this information, spring and autumn appear to be the seasons where most classrooms consistently maintain ideal temperature ranges. Spring might have a slight edge between these two due to the excellent performance across multiple classroom sets (C1, C2, and C3).

Therefore, based on the data provided, spring could be considered the "best" season overall for maintaining ideal temperature ranges across different classrooms. However, it is important to note that performance can vary significantly between individual classrooms and school buildings.

Relative Humidity

Tables 5.9 and 5.10 show the distribution of RH ranges across four various schools during multiple seasons.

TABLE 5.9: RH Cuts in Christchurch Schools (Part 1) (09:00 - 15:00 School Days Only)

School	Room	Season	Below 40	[40-60[	[60-70[	Above 70
C1	1	Spring		100%		
		Summer		93%	7%	
		Autumn		26%	74%	
		Winter	3%	97%		
C1	2	Spring	na	na	na	na
		Summer		91%	9%	
		Autumn	na	na	na	na
		Winter		84%	16%	
C1	5	Spring	3%	97%		
		Summer	na	na	na	na
		Autumn		78%	22%	
		Winter			100%	
C2	1	Spring	26%	74%		
		Summer		67%	33%	
		Autumn	na	na	na	na
		Winter	na	na	na	na
C2	2	Spring	57%	43%		
		Summer	na	na	na	na
		Autumn	na	na	na	na
		Winter				100%
C2	3	Spring	16%	84%		
		Summer	na	na	na	na
		Autumn	na	na	na	na
		Winter	na	na	na	na

Based on the data (Table 5.9), C1-1 outperforms the others. It boasts the highest percentage in the optimal range for both summer (93%) and winter (97%). Although C1-1's autumn performance might appear subpar at first glance (26% in [40-60[), it is preferable to C1-5's winter performance, which has 0% in the optimal range. Consistency is another strength of C1-1, with two seasons (summer and winter) having over 90% in the optimal range. In contrast, while C1-5 performs well in spring and autumn, its winter performance (100% in [60-70]) is now considered the worst among all measurements. C1-2, despite performing well, fails to reach the high percentages in the optimal range achieved by C1-1. In conclusion, with the new understanding of optimal humidity ranges, C1-1 performs better overall. It

consistently maintains high percentages in the optimal [40-60[range across seasons, particularly in summer and winter, and even its autumn performance is preferable to having higher humidity levels.

When comparing (Table 5.9) C2-3 with other classrooms during the spring season, its superior performance becomes evident. C2-3 maintains 84% of its RH in the optimal range, with only 16% below 40. In contrast, C2-1 in spring achieves 74% in the optimal range with 26% below 40. This comparison shows that Room 3 outperforms Room 1 by 10% in the optimal range. The difference is even more pronounced when comparing C2-3 to C2-2 in spring. While Room 3 maintains its 84% optimal and 16% below 40, Room 2 only manages 43% in the optimal range with a substantial 57% below 40. This represents a significant 41% advantage for Room 3 in the optimal range.

Compared to different seasons, C2-3's spring performance surpasses C2-1's summer results. Room 3 maintains its 84% optimal and 16 below 40, while Room 1 in summer achieves 67% in the optimal range with 33% in the less desirable [60-70[range. This comparison reveals that Room 3 outperforms Room 1's summer performance by 17% in the optimal range. it is worth noting that C2-2 in winter shows the worst performance overall, with 100% of its RH above 70, far from the optimal range.

In conclusion, C2-3 demonstrates the best overall performance in RH control. It has the highest percentage (84%) in the optimal [40-60[range among all measurements. It also maintains the lowest percentage (16%) in the less desirable range for spring measurements. The consistency and high percentage in the optimal range make C2-3 the best-performing classroom regarding RH control.

TABLE 5.10: RH Cuts in Christchurch Schools (Part 2) (09:00 - 15:00 School Days Only)

School	Room	Season	Below 40	[40-60[	[60-70[	Above 70
C3	2	Spring	18%	82%		
		Summer		20%	56%	
		Autumn		100%		
		Winter		94%	6%	
C3	3	Spring	24%	76%		
		Summer		100%		
		Autumn	na	na	na	na
		Winter		100%		
C3	4	Spring	20%	80%		
		Summer		99%	1%	
		Autumn			100%	
		Winter		48%	52%	
C4	1	Spring	10%	90%		
		Summer		58%	42%	
		Autumn		98%	2%	
		Winter		100%		
C4	2	Spring	15%	85%		
		Summer		33%	36%	31%
		Autumn			100%	
		Winter			76%	24%
C4	3A	Spring	34%	66%		
		Summer		51%	46%	3%
		Autumn		100%		
		Winter	64%	36%		
C4	3B	Spring	37%	64%		
		Summer		58%	41%	1%
		Autumn		100%		
		Winter	68%	32%		

Based on the data (Table 5.10), C3-3 maintains 100% in the optimal range for both summer and winter and 76% in spring. This consistency is unmatched by other classrooms. C3-3 has only one season (spring) with measurements outside the optimal range. C3-2 has three seasons with measurements outside the optimal range. C3-4 has all four seasons with measurements outside the optimal range.

During summer, C3-3 (100% optimal) outperforms C3-2 (20% optimal, 56% in [60-70[) and C3-4 (99% optimal, 1% in [60-70[). In winter, C3-3 (100% optimal) outperforms C3-2 (94% optimal, 6% in [60-70[) and C3-4 (48% optimal, 52% in [60-70[).

Unlike C3-4, which has 100% in the [60-70[range in autumn, C3-3 never has 100% of measurements in an undesirable range.

In conclusion, C3-3 demonstrates the best overall performance in RH control. It consistently maintains high percentages in the optimal [40-60[range across seasons, particularly in summer and winter with 100% optimal conditions. It also has the highest average percentage in the optimal range (92%) and the fewest measurements in undesirable ranges. The consistency and high percentage in the optimal range make C3-3 the best-performing classroom in terms of RH control.

Based on the data (**Table 5.10**), C4-1 performs better in RH control compared to the other rooms. C4-1 maintains RH in the optimal [40-60[range for all seasons, with percentages ranging from 58% to 100%. Other rooms have seasons where they completely miss this optimal range. C4-1 averages 86.5% in the optimal range across all seasons. This is significantly higher than other rooms: C4-2 at 29.5%, C4-3A at 63.25%, and C4-3B at 63.5%.

C4-1 never experiences RH above 70% or below 40% in any season except spring (10% below 40). Other rooms have more extreme conditions. For example, C4-2 has 31% above 70% in summer and 24% above 70% in winter, while C4-3A and 3B have significant percentages below 40% in spring and winter.

In problematic seasons like summer, when high humidity is often an issue, C4-1 performs better with 58% optimal and 42% in [60-70[, compared to C4-2 with 33% optimal, 36% in [60-70[, and 31% above 70%. In winter, when low humidity can be a problem, C4-1 maintains 100% optimal conditions, while other rooms struggle with either high humidity (C4-2) or low humidity (C4-3A and 3B).

Unlike C4-2, which has 100% in the [60-70[range in autumn, C4-1 never has 100% of measurements in an undesirable range. In conclusion, C4-1 demonstrates the best overall performance in RH control. It consistently maintains high percentages in the optimal [40-60[range across all seasons, has the highest average percentage in the optimal range and avoids extreme or prolonged undesirable conditions better than the other rooms.

Based on the analysis, it is clear that performance varies across different classrooms

and buildings. However, if we need to identify the "best" season overall, spring appears to be the strongest candidate. While autumn also shows good performance in some cases, spring seems to have a slight edge overall. Summer generally shows lower performance compared to other seasons, with some exceptions. Winter shows mixed results, with some classrooms performing well and others struggling significantly.

It is important to note that performance can vary significantly between individual classrooms and school buildings. However, based on the overall trends observed across the different data sets, spring is the season that most consistently maintains ideal RH ranges across various classrooms.

Carbon dioxide

Tables 5.11 and 5.12 present various classrooms in four different Christchurch schools across different seasons, categorizing the percentage of time CO₂ levels fall into specific ranges.

TABLE 5.11: CO₂ Cuts in Christchurch Schools (Part 1) (09:00 - 15:00 School Days Only)

School	Room	Season	[400-800]	[800-1000]	[1000-1500]	[1500-2000]	[2000-3000]	[3000-5000]
C1	1	Spring	8%	12%	33%	30%	17%	
		Summer	4%	14%	53%	25%	4%	
		Autumn			69%	31%		
		Winter	3%	5%	20%	60%	12%	
C1	2	Spring	na	na	na	na	na	na
		Summer		6%	44%	41%	9%	
		Autumn	na	na	na	na	na	na
		Winter		1%	8%	41%	48%	2%
C1	5	Spring	6%	8%	23%	26%	24%	13%
		Summer	na	na	na	na	na	na
		Autumn	18%	11%	60%	11%		
		Winter					100%	
C2	1	Spring	16%	5%	31%	26%	22%	
		Summer	1%	6%	18%	30%	46%	
		Autumn	na	na	na	na	na	na
		Winter	na	na	na	na	na	na
C2	2	Spring	43%	26%	30%	1%		
		Summer	na	na	na	na	na	na
		Autumn	na	na	na	na	na	na
		Winter	100%					
C2	3	Spring	63%	18%	17%	2%		
		Summer	na	na	na	na	na	na
		Autumn	na	na	na	na	na	na
		Winter	na	na	na	na	na	na

C1-1 (Table 5.11) CO₂ levels frequently exceed recommended limits, with winter being particularly problematic as levels exceed 1500 ppm 72% of the time. C1-2 shows high CO₂ concentrations, especially in winter when levels surpass 1500 ppm 91% of the time. C1-5 experiences varied conditions, with winter being the most concerning as CO₂ levels exceed 2000 ppm 100% of the time. C2-1 also struggles with high CO₂ levels, particularly in summer.

Many classrooms frequently exceed these recommended limits, indicating potential issues with IAQ and ventilation.

TABLE 5.12: CO₂ Cuts in Christchurch Schools (Part 2) (09:00 - 15:00 School Days Only)

School	Room	Season	[400-800[	[800-1000[	[1000-1500[	[1500-2000[	[2000-3000[	[3000-5000[
C3	2	Spring	21%	28%	21%	7%	19%	3%
		Summer	49%	16%	26%	9%		
		Autumn	83%	17%				
		Winter	6%	4%	19%	21%	43%	6%
C3	3	Spring	52%	15%	22%	7%	4%	
		Summer		3%	17%	14%	60%	6%
		Autumn	na	na	na	na	na	na
		Winter	24%	21%	20%	35%		
C3	4	Spring	16%	4%	16%	18%	39%	7%
		Summer			6%	9%	35%	50%
		Autumn						100%
		Winter	1%	5%	10%	16%	33%	35%
C4	1	Spring	61%	19%	17%	2%		
		Summer	73%	14%	13%			
		Autumn	32%	68%				
		Winter	14%	19%	17%	14%	21%	15%
C4	2	Spring	88%	6%	6%			
		Summer	95%	5%				
		Autumn			64%	36%		
		Winter	100%					
C4	3A	Spring	94%	4%	2%			
		Summer	91%	9%				
		Autumn	99%	1%				
		Winter	55%	28%	13%	4%		
C4	3B	Spring	94%	4%	2%			
		Summer	92%	8%				
		Autumn	99%	1%				
		Winter	56%	29%	12%	3%		

C3-3 (Table 5.12) performs well in spring but poorly in summer, with CO₂ levels surpassing 1500 ppm 80% of the time. C3-4 consistently struggles with air quality, particularly in autumn when CO₂ levels exceed 3000 ppm 100% of the time. C4-1 maintains good air quality in spring, summer, and autumn but faces challenges in winter. C4-2 performs excellently in spring, summer, and winter but experiences

higher CO₂ levels in autumn. C4-3A and C4-3B (a duplicate for quality assurance) demonstrate consistently good air quality across all seasons, with CO₂ levels rarely exceeding recommended limits. Overall, while some classrooms maintain acceptable air quality, others frequently exceed the recommended CO₂ levels, indicating potential ventilation issues that vary by season and classroom.

Based on the information, it is challenging to definitively state which season is the "best" overall, as performance varies significantly across different classrooms and buildings. However, we can draw some general conclusions:

Spring appears to be the season with the best overall performance. Several classrooms (e.g., C3-3, C4-1, C4-2, C4-3A, and C4-3B) maintain good air quality during this season. Summer shows mixed results, with some classrooms performing well (e.g., C4-1, C4-2, C4-3A, and C4-3B) and others struggling (e.g., C2-1, C3-3). Autumn generally shows moderate performance, with some classrooms maintaining good air quality (e.g., C4-1, C4-3A, and C4-3B) while others face challenges (e.g., C3-4). Winter is often the most problematic season, with many classrooms experiencing high CO₂ levels (e.g., C1-1, C1-2, C1-5).

Given these observations, spring could be considered the "best" season overall for maintaining good air quality across different classrooms. However, it is crucial to note that this is a generalization, and individual classrooms may perform differently. The data suggests that ventilation issues are prevalent and vary significantly by season and classroom, indicating a need for improved ventilation strategies, especially during colder months when windows are likely to be closed more often.

IEM reporting in Dunedin schools

The average weekly temperature, RH, and CO₂ levels during school hours (Monday 09:00 to Friday 15:00) for four schools in Dunedin (D1, D2, D3 and D4), can be found in **Appendix F.3**.

H2-2(A and B) is the classroom in Hawke's Bay where two IEMs are installed. These devices consistently show the same results, confirming the IEM's robustness.

Temperature

Tables 5.13 and 5.14 provide an overview of the classroom temperature conditions across different rooms and seasons, showing percentages of time spent within various temperature ranges.

TABLE 5.13: *Temperature Cuts in Dunedin Schools (Part 1) (09:00 - 15:00 School Days Only)*

School	Room	Season	Below 16	[16-18[	[18-24[	[24-28[	Above 28
D1	1	Spring			100%		
		Summer			46%	54%	
		Autumn			100%		
		Winter			100%		
D1	2	Spring		22%	78%		
		Summer			63%	37%	
		Autumn			100%		
		Winter			100%		
D1	3A	Spring		2%	98%		
		Summer			55%	45%	
		Autumn			100%		
		Winter	na	na	na	na	na
D1	3B	Spring		3%	97%		
		Summer			61%	39%	
		Autumn			100%		
		Winter	na	na	na	na	na
D1	4	Spring		3%	97%		
		Summer			64%	36%	
		Autumn			100%		
		Winter			75%	25%	
D2	1	Spring			89%	11%	
		Summer			56%	42%	
		Autumn			100%		
		Winter			67%	34%	
D2	2	Spring		1%	78%	21%	
		Summer			55%	45%	
		Autumn			100%		
		Winter	1%	2%	57%	38%	
D2	4	Spring	2%	5%	93%		
		Summer			67%	33%	
		Autumn			100%		
		Winter	2%	4%	94%		

Based on the data (Table 5.13), D1-1 performs exceptionally well in maintaining optimal temperatures across various seasons. D1-1 stands out for its consistency

across seasons. During spring, autumn, and winter, D1-1 achieves outstanding performance, with all recorded temperatures falling within the optimal range of 18-24 °C. In contrast, D1-2 only manages 78% within this range in spring, with 22% of temperatures falling below. Rooms 3A and 3B perform slightly better, maintaining 98% and 97% optimal temperatures in spring, yet still have small portions falling below the optimal range. D1-4, which only has winter data, shows 75% of temperatures within the optimal range and 25% above it, further highlighting D1-1's excellence.

Although D1-1's performance during summer is not perfect, with 46% of temperatures in the optimal range and 54% in the 24-28 °C range, it remains comparable to or better than other rooms. D1-2, for instance, achieves 63% optimal and 37% in the 24-28 °C range. Similarly, D1-3A records 55% optimal and 45% in the 24-28 °C range, while D1-3B shows 61% optimal and 39% in the 24-28 °C range. D1-4 fares better, with 64% optimal but still 36% in the 24-28 °C range. Despite the disparity, D1-1's summer statistics highlight its capability to avoid extreme temperatures.

D2-1 never experiences temperatures below 16 °C or above 28 °C in any season, setting a benchmark for temperature control. Other rooms in the dataset occasionally record temperatures below 16 °C, particularly during certain seasons, underscoring D2-1's superior performance. D2-1 provides data for all four seasons, offering a comprehensive view of its year-round performance. This extensive data availability allows for a more accurate assessment than rooms with incomplete seasonal recordings.

Comparing these results, D2-4 performs the best overall for several key reasons. Firstly, it consistently maintains the highest percentage of time within the optimal temperature range for three out of four seasons (spring, summer, and winter). D2-4 also demonstrates remarkable consistency across seasons, with 93% or more of the time spent within the optimal range throughout spring, autumn, and winter. Additionally, it experiences fewer extreme temperatures, with less time spent below 16 °C or above 28 °C compared to the other rooms. Quantitative examples further support D2-4's superior performance: in spring, it remains within the optimal range 93% of the time, outperforming D2-1 (89%) and D2-2 (78%); in summer, it maintains optimal temperatures 67% of the time, surpassing both D2-1 (56%) and D2-2 (55%);

and in winter, it achieves an impressive 94% within the optimal range, significantly higher than D2-1 (67%) and D2-2 (57%). D2-4 also experiences minimal extreme cold, with only 2% of time below 16 °C in spring and winter, compared to D2-2's 1% below 16 °C in winter and 1% in the 16-18 °C range in spring. While all rooms perform equally well in autumn (100% within optimal range), D2-4's superior performance in other seasons establishes it as the best-performing class overall for maintaining optimal learning temperatures.

TABLE 5.14: *Temperature Cuts in Dunedin Schools (Part 2) (09:00 - 15:00 School Days Only)*

School	Room	Season	Below 16	[16-18[	[18-24[	[24-28[	Above 28
D3	1	Spring	6%	19%	76%		
		Summer			47%	48%	5%
		Autumn	na	na	na	na	na
		Winter		8%	92%		
D3	2A	Spring	3%	1%	92%	4%	
		Summer			56%	44%	
		Autumn			100%		
		Winter		2%	67%	32%	
D3	2B	Spring	3%	1%	92%	5%	
		Summer			50%	50%	
		Autumn			100%		
		Winter		2%	66%	32%	
D3	3	Spring	3%	11%	85%	1%	
		Summer			66%	34%	
		Autumn			100%		
		Winter		6%	94%		
D3	4	Spring	2%	1%	96%	1%	
		Summer			35%	60%	5%
		Autumn			100%		
		Winter			89%	11%	
D4	1	Spring	31%	26%	43%		
		Summer	na	na	na	na	na
		Autumn		50%	50%		
		Winter	9%	15%	76%		

Comparing these results (Table 5.14), D3-3 performs the best overall for several reasons. It demonstrates consistency across seasons, maintaining a high percentage within the optimal range throughout the year, with 85% or more in spring, autumn, and winter. D3-3 significantly outperforms other rooms in summer, with 66% of time in the optimal range, and exhibits balanced performance across all seasons. Quantitative examples support this conclusion: In summer, D3-3 is within the

optimal range 66% of the time, compared to 47% for D3-1, 53% for D3-2, and only 35% for D3-4. In winter, D3-3 is within the optimal range 94% of the time, outperforming all other rooms. In spring, D3-3 (85%) performs better than D3-1 (76%) and is close to D3-2 (92%) and D3-4 (96%). D3-3 also has fewer temperatures outside the optimal range in summer than other rooms, with 0% above 28 °C, while D3-1 and D3-4 have 5% above 28 °C. In winter, D3-3 has only 6% of time in the 16-18 °C range, compared to 8% for D3-1 and 11% above 24 °C for D3-4. While D3-4 performs slightly better in spring and equally well in autumn, its poor performance in summer significantly reduces its overall effectiveness. D3-3's superior performance in summer and winter, as well as its overall consistency across all seasons, makes it the best-performing classroom in terms of maintaining optimal temperatures for learning. Additionally, D3-3 experiences fewer extreme temperatures throughout the year, providing a more stable and comfortable learning environment.

Based on the information provided, it is difficult to definitively state which season is the "best" as the performance of the rooms varies across seasons. However, we can draw some conclusions:

- Autumn seems to be the most consistent season across all rooms, with high percentages of time within the optimal temperature range.
- Winter performs well for most rooms, particularly D3-3 and D3-4.
- Spring also shows generally good performance across rooms.
- Summer appears to be the most challenging season, with lower percentages of time in the optimal range for all rooms.

Overall, autumn and winter seem to be the seasons when the rooms perform best at maintaining optimal temperatures. Summer is the season that presents the most difficulties in temperature control.

It is important to note that D3-3 is highlighted as the best-performing room overall due to its consistency across all seasons and its particularly strong performance in summer compared to other rooms. This suggests that D3-3 might offer the most comfortable learning environment throughout the year, despite the challenges of different seasons.

Relative Humidity

Tables 5.15 and 5.16 examine the RH levels in classrooms across different Dunedin schools.

TABLE 5.15: *RH Cuts in Dunedin Schools (Part 1) (09:00 - 15:00 School Days Only)*

School	Room	Season	Below 40	[40-60[	[60-70[	Above 70
D1	1	Spring	86%	14%		
		Winter	26%	74%		
D1	2	Spring	9%	91%		
		Winter	10%	90%		
D1	3A	Spring	16%	84%		
D1	3B	Spring	11%	89%		
D1	4	Spring	11%	89%		
		Summer		59%	41%	
		Winter	74%	26%		
D2	1	Spring	83%	17%		
		Summer		92%	8%	
		Autumn		73%	27%	
		Winter	38%	62%		
D2	2	Spring	81%	19%		
		Winter	45%	55%		
D2	4	Spring	29%	71%		
		Summer		47%	53%	
		Autumn			100%	

Based on the provided data (**Table 5.15**), D1-2 performs better overall in maintaining optimal RH levels. D1-2 consistently maintains RH levels within the optimal 40-60% range for a higher percentage of time across all seasons than other rooms. This consistency is evident in its performance during individual seasons.

In spring, D1-2 outperforms all other rooms with 91% of time in the optimal range, compared to D1-1 (14%), D1-3A (84%), D1-3B (89%), and D1-4 (89%). During summer, D1-2, along with Rooms 1, 3A, and 3B, maintains 100% of time in the optimal range, while D1-4 only achieves 59%. In autumn, all rooms, including D1-2, perform equally well with 100% of time in the optimal range. Winter sees D1-2 maintaining 90% of time in the optimal range, significantly outperforming D1-1

(74%) and D1-4 (26%).

D1-2 also spends minimal time in suboptimal RH ranges across seasons. In spring, it has only 9% below 40% RH, compared to much higher percentages for other rooms (86% for D1-1, 16% for D1-3A, 11% for D1-3B, and 11% for D1-4). Similarly, in winter, D1-2 has only 10% below 40% RH, compared to 26% for D1-1 and 74% for D1-4.

Notably, D1-2 never experiences RH levels above 60%, unlike D1-4, which has 41% of time in the 60-70% range during summer. Furthermore, D1-2 provides data for all four seasons, allowing for a comprehensive assessment of its performance throughout the year.

In conclusion, D1-2 demonstrates superior performance in maintaining optimal RH levels across all seasons, with consistently high percentages in the 40-60% range and minimal time spent in suboptimal conditions. This makes it the best-performing classroom regarding humidity control according to ASHRAE standards.

Based on the data provided (**Table 5.15**), classroom D2-4 generally performs better in terms of maintaining optimal RH levels according to ASHRAE standards. The ASHRAE standards recommend an RH range of 40-60% when the temperature is between 18 °C and 24 °C. Classroom D2-4 shows the highest percentage of time within or close to this optimal range across different seasons. For example, in spring, D2-4 maintains the optimal RH range 71% of the time, significantly higher than D2-1 (17%) and D2-2 (19%). In summer, although D2-4's performance is not as good as the other rooms, it still maintains the optimal range 47% of the time, with the remaining 53% only slightly above the optimal range at 60-70%. Autumn data for D2-4 shows 100% of the time in the 60-70% range, which is close to the optimal range and better than D2-1's performance (73% optimal, 27% in 60-70% range). While winter data is unavailable for D2-4, its overall performance across the other seasons suggests it is the best-performing classroom in maintaining appropriate humidity levels.

TABLE 5.16: RH Cuts in Dunedin Schools (Part 2) (09:00 - 15:00 School Days Only)

School	Room	Season	Below 40	[40-60[	[60-70[	Above 70
D3	1	Summer		50%	50%	
		Winter		99%	1%	
D3	2A	Spring	51%	49%		
		Summer		71%	29%	
		Winter	36%	64%		
D3	2B	Spring	49%	51%		
		Summer		69%	31%	
		Winter	33%	67%		
D3	3	Spring	2%	98%		
		Summer		87%	13%	
		Autumn			100%	
D3	4	Spring	35%	65%		
		Summer		85%	15%	
		Autumn		59%	41%	
		Winter	6%	94%		
D4	1	Spring	8%	92%		
		Autumn			100%	
		Winter	9%	91%		

Based on the data provided (Table 5.16), classroom D3-3 generally performs the best to maintain optimal RH levels according to ASHRAE standards, which recommend a RH range of 40-60% when the temperature is between 18 °C and 24 °C. D3-3 consistently shows high percentages of time within or close to this optimal range across different seasons. In spring, D3-3 maintains the optimal RH range 98% of the time, significantly outperforming other classrooms. During summer, it maintains the optimal range 87% of the time, which is the second-best performance after D3-4 (85%). In autumn, while it is outside the optimal range, it remains in the close 60-70% range 100% of the time. Winter performance is excellent, with 100% of the time in the optimal range. D3-3's overall performance is more consistent and generally better than other classrooms. For comparison, D3-1 performs well in spring and winter but struggles in summer, with only 50% in the optimal range. D3-2A and D3-2B (duplicates for quality assurance) show similar patterns but have more time below the optimal range in spring and winter. D3-4 also performs well but has more fluctuations across seasons compared to D3-3. Therefore, D3-3 can be considered the best-performing classroom for maintaining appropriate humidity levels throughout the year.

Based on the analysis of the data from schools D1, D2, and D3, it appears that autumn is generally the best season for maintaining optimal RH levels across classrooms.

- In School D1, all rooms maintain 100% of the time in the optimal 40-60% RH range during autumn.
- In School D2, Room 1 and Room 2 both maintain 100% of the time in the optimal range during autumn. Room 4 is slightly above the optimal range but still maintains 100% in the close 60-70% range.
- In School D3, Room 2A and 2B both maintain 100% of the time in the optimal range during autumn. Room 3 is slightly above but maintains 100% in the close 60-70% range.

Autumn consistently shows the best or near-best performance across all schools and classrooms. Other seasons show more variability:

- Spring often has issues with low humidity (below 40%) in many classrooms.
- Summer sometimes sees humidity levels creeping above the optimal range in some classrooms.
- Winter performance is mixed, with some classrooms maintaining good levels and others struggling with low humidity.

Therefore, autumn emerges as the season when most classrooms across all schools can consistently maintain optimal or near-optimal humidity levels.

Carbon dioxide

Tables 5.17 and 5.18 present data regarding CO₂ levels in various classrooms across different seasons and rooms in Schools D1 and D2.

TABLE 5.17: CO₂ Cuts in Dunedin Schools (Part 1) (09:00 - 15:00 School Days Only)

School	Room	Season	[400-800[	[800-1000[	[1000-1500[	[1500-2000[	[2000-3000[	[3000-5000]
D1	1	Spring	22%	20%	49%	9%		
		Summer	60%	18%	17%	5%		
		Autumn	38%	14%	48%			
		Winter	7%	23%	48%	22%		
D1	2	Spring	10%	21%	41%	27%	2%	
		Autumn	33%	15%	38%	14%		
		Winter	26%	17%	46%	6%	5%	
D1	3A	Spring	90%	6%	4%			
		Autumn	61%	10%	18%	11%		
D1	3B	Spring	88%	7%	5%			
		Autumn	61%	11%	18%	10%		
D1	4	Spring	15%	18%	39%	14%	14%	
		Summer	32%	16%	41%	10%	1%	
		Winter	44%	23%	33%			
D2	1	Autumn			33%	67%		
		Winter	2%	22%	47%	29%		
D2	2	Spring	35%	14%	28%	18%	5%	
		Autumn	24%	47%	29%			
		Winter	19%	9%	48%	24%		
D2	4	Spring	41%	30%	29%			
		Summer	27%	34%	31%	8%		
		Winter	46%	8%	21%	14%	11%	

Based on the data provided (Table 5.17), classroom D1-3A (and its duplicate D1-3B for quality assurance) performs the best in maintaining optimal CO₂ levels within the 400-800 ppm range. This classroom consistently shows the highest percentage of time within the optimal range across different seasons. In spring, D1-3A maintains the optimal range 90% of the time, significantly outperforming other classrooms such as D1-1 (22%), D1-2 (10%), and D1-4 (15%). During summer, D1-3A achieves a perfect score with 100% of the time in the optimal range, matching only its duplicate D1-3B. Autumn performance is also strong, with 61% of the time in the optimal range, second only to D1-4's exceptional 98%. Unfortunately, winter data is not available for D1-3A and D1-3B. In comparison, other classrooms often struggle to maintain optimal CO₂ levels. For instance, D1-1 only reaches the optimal range 22% of the time in spring, 60% in summer, 38% in autumn, and a mere 7% in winter. D1-2

shows similar variability, with its best performance in summer (92%) but much lower percentages in other seasons. D1-4 has inconsistent performance across seasons, ranging from 15% in spring to 98% in autumn. The consistent high performance of D1-3A across available seasons, especially its perfect score in summer, makes it the best-performing classroom to maintain appropriate CO₂ levels.

Based on the data provided (**Table 5.17**), classroom D2-1 generally performs the best in maintaining optimal CO₂ levels within the 400-800 ppm range. This classroom shows consistently high percentages of time within the optimal range across different seasons, with exceptional performance in spring and summer. In spring, D2-1 maintains the optimal range 73% of the time, outperforming D2-2 (35%) and D2-4 (41%). During summer, D2-1 achieves a perfect score with 100% of the time in the optimal range, matching D2-2 but significantly better than D2-4 (27%). However, D2-1's performance drops significantly in autumn and winter. In autumn, it spends no time in the optimal range, with 33% in the 1000-1500 ppm range and 67% in the 1500-2000 ppm range. Winter performance is also poor, with only 2% in the optimal range. Despite these seasonal fluctuations, D2-1's strong performance in spring and summer sets it apart. In comparison, D2-2 shows more consistent but generally lower percentages in the optimal range across seasons, except for the perfect summer performance. D2-4 demonstrates the most inconsistent performance, with its best being only 46% in the optimal range during winter. Despite poor autumn and winter results, the exceptional performance of D2-1 in spring and summer makes it the best-performing classroom overall in maintaining appropriate CO₂ levels.

TABLE 5.18: CO₂ Cuts in Dunedin Schools (Part 2) (09:00 - 15:00 School Days Only)

School	Room	Season	[400-800[	[800-1000[	[1000-1500[	[1500-2000[	[2000-3000[	[3000-5000]
D3	1	Spring	32%	12%	42%	14%		
		Summer	22%	21%	26%	24%	7%	
		Winter	11%	4%	35%	47%	3%	
D3	2A	Spring	38%	28%	24%	10%	1%	
		Summer	52%	16%	31%	1%		
		Autumn	47%	7%	10%	36%		
		Winter	37%	19%	28%	14%	2%	
D3	2B	Spring	39%	29%	22%	9%	1%	
		Summer	51%	17%	31%	1%		
		Autumn	46%	5%	14%	35%		
		Winter	37%	20%	28%	14%	1%	
D3	3	Spring	24%	14%	38%	24%		
		Summer	45%	35%	20%			
		Autumn	18%	11%	71%			
		Winter	4%	8%	40%	44%	4%	
D3	4	Spring	45%	18%	31%	6%		
		Summer	41%	26%	33%			
		Autumn		15%	53%	4%	28%	
		Winter	29%	18%	36%	17%		
D4	1	Spring	14%	14%	56%	11%	5%	
		Autumn				100%		
		Winter	46%	8%	21%	14%	11%	

Based on the provided data (Table 5.18), D3-2A and 2B in School D3 generally perform better in maintaining optimal CO₂ levels (400-800 ppm) across seasons. These rooms consistently show higher percentages of time within the optimal range compared to other rooms. For example, in summer, D3-2A and 2B spend 52% and 51% of the time, respectively, in the optimal range, which is significantly higher than other rooms. In spring, these rooms maintain 38% and 39% of time in the optimal range, again outperforming other rooms. D3-4 also shows good performance in spring and summer, with 45% and 41% of time in the optimal range, respectively. In contrast, D3-1 and D3-3 generally have lower percentages in the optimal range, often falling into higher CO₂ concentration brackets. For instance, D3-1 in winter spends only 11% of time in the optimal range, with 47% of time in the 1500-2000 ppm range. D3-3 in autumn spends 71% of time in the 1000-1500 ppm range, well above the optimal level. These differences could be due to ventilation efficiency, room occupancy, or activities conducted in each space.

Based on the data provided (Table 5.18), summer appears to be the best season overall

for maintaining optimal CO₂ levels (400-800 ppm) across the classrooms in School D3. During summer, most rooms show their highest percentages of time within the optimal range. For example, D3-2A and 2B achieve their best performance in summer, with 52% and 51% of time in the optimal range, respectively. D3-3 also performs well in summer, with 45% of time in the optimal range, its highest percentage across all seasons. Even D3-1, which generally has lower percentages in the optimal range, shows improvement in summer with 22% of time in the optimal range, compared to only 11% in winter. This trend suggests that summer conditions, possibly due to increased NV through open windows, contribute to better IAQ regarding CO₂ levels. Spring is the second-best season for most rooms, followed by autumn and winter, which generally perform poorly in maintaining optimal CO₂ levels.

5.4 Auckland - 29/8/2022 to 25/6/2024 (post COVID-19)

This follow-up study in Auckland after the COVID-19 restrictions were lifted presents a unique opportunity to assess the impact of the pandemic on IEQ in educational settings. The research, conducted at a primary school using IEMs, aims to provide valuable insights into how the school environment has adapted in the wake of the global health crisis.

The study's dual purpose is particularly noteworthy. By collecting data on indoor environmental conditions, researchers can immediately understand how the school's IEQ has changed since the pre-pandemic period. This information is crucial to evaluate the effectiveness of any COVID-19 mitigation strategies that may have been implemented, such as improved ventilation practices or changes in occupancy patterns.

Moreover, establishing a post-pandemic baseline is invaluable for future cognitive studies, as outlined in Chapter 7. This baseline will allow researchers to track long-term trends in IEQ and its potential effects on student and teacher performance, health, and well-being.

The assumption of the study regarding an increased awareness of ventilation practices among teachers is particularly intriguing. Given the extensive publications, interventions, and guidance provided by the MoE, government agencies, and health

organisations during the pandemic, it is reasonable to hypothesise that teachers may have become more aware of the importance of proper ventilation. This increased awareness could improve classroom air quality through frequent window opening and other ventilation strategies.

However, it is essential to note that this assumption must be carefully evaluated against the collected data. Weather conditions, building design, and individual teacher behaviours may all influence the observed ventilation practices. Additionally, the study may reveal whether any improvements in ventilation practices have been sustained over time or if there has been a gradual return to pre-pandemic habits.

Using the same IEMs in this follow-up study ensures consistency with previous data collection methods, allowing direct comparisons between pre- and post-pandemic conditions. This continuity in methodology strengthens the reliability of the findings and enhances the ability to draw meaningful conclusions about changes in the school's indoor environment.

As the research progresses, it will be crucial to consider the quantitative data collected by the IEM devices and the qualitative information gathered from teachers. This will include surveys to assess their perceptions of IAQ, their understanding of ventilation best practices, and any challenges they face in implementing these practices consistently (Chapter 6).

Ultimately, this follow-up study has the potential to provide valuable insights into the lasting impacts of COVID-19 on school environments and to inform future policies and practices for maintaining healthy indoor spaces in educational settings.

5.4.1 Meteorological reporting: Outside compartment

For a more comprehensive understanding of the meteorological context, readers should refer to **Appendix E Section E.2**. This section provides detailed data, analyses, and **visualizations** of relevant meteorological parameters, offering insights into seasonal patterns and their impact on IEQ in educational settings. This supplementary information enhances the interpretation of the main text's strategies and recommendations, facilitating a nuanced approach to managing

indoor environments across diverse climatic conditions.

Ambient temperature (E.1) patterns in the region exhibit distinct seasonal variations. Winter experiences the lowest temperatures, with averages hovering around 12-13 °C. As spring arrives, there is a moderate increase in temperature, typically reaching around 15 °C. Summer brings the highest temperatures of the year, with peaks around 19-20 °C, and is characterized by relatively stable conditions. Autumn is a transitional period, with intermediate temperatures ranging from 15-17 °C. Notably, autumn 2023 was slightly warmer than the projections for autumn 2024, highlighting subtle year-to-year variations within the overall seasonal pattern—clear cyclic patterns with cold winters, hot summers, and transitional temperatures in spring and autumn.

RH (E.2) in the region exhibits distinct seasonal patterns and variability. Winter experiences the highest RH levels, averaging around 84% with moderate fluctuations. As spring arrives, RH slightly decreases to around 79-80%, showing noticeable variability. Summer brings the lowest RH levels, ranging between 73-83%, indicating significant fluctuations and high variability throughout the season. Autumn is a transitional period with intermediate RH levels around 82-83%, accompanied by substantial variability. Overall, the trend shows that RH is highest in winter and lowest in summer, with spring and autumn presenting transitional values and notable variability.

Rainfall (E.3) patterns in the region demonstrate considerable seasonal variability and fluctuations. Winter and autumn experience moderate rainfall, typically ranging from approximately 3-4.5 mm, with high variability observed during these seasons. Spring tends to have lower rainfall amounts, generally around 2-4 mm, but exhibits significant fluctuations. Summers show the most varied rainfall patterns, with a notable peak of around 8 mm observed in summer 2023, followed by a dramatic drop to nearly 1-2 mm in summer 2024. This stark contrast between consecutive summers highlights the unpredictable nature of rainfall during this season. The overall trend indicates that summers generally exhibit varying rainfall patterns, with broader fluctuations observed across all seasons.

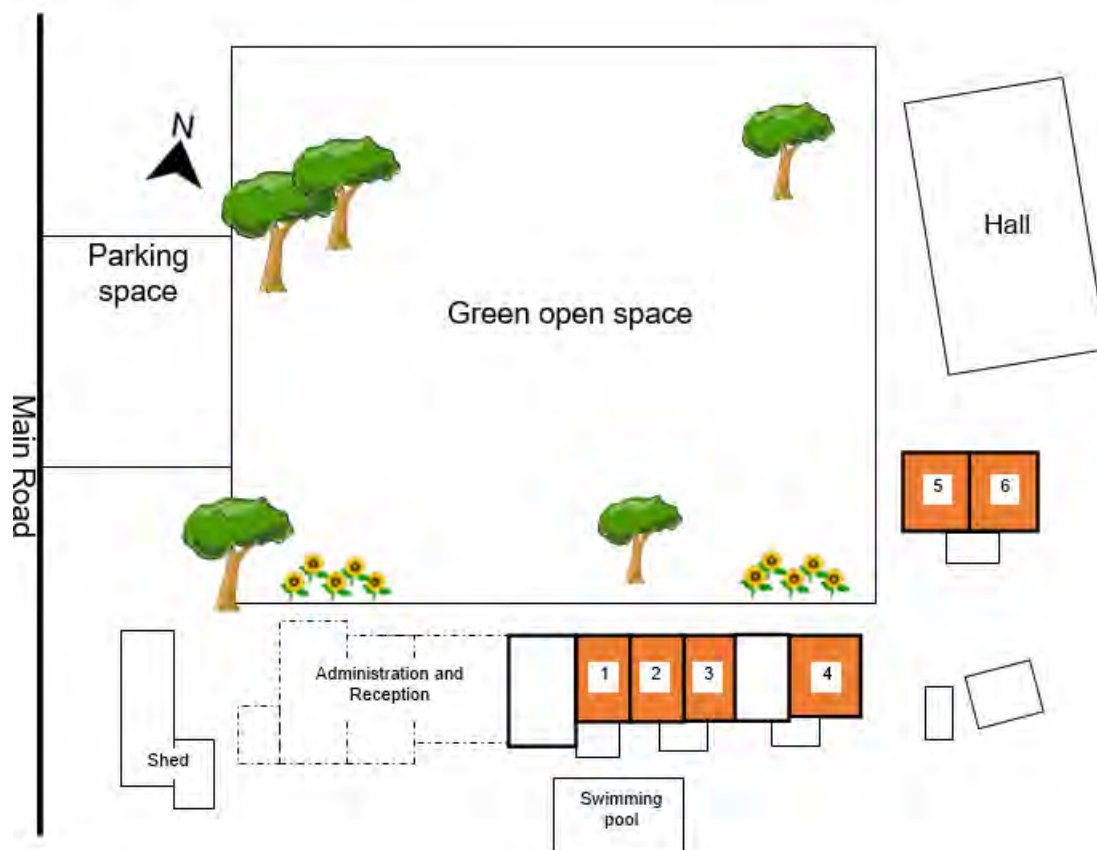
Wind patterns (E.4) in the region demonstrate a relatively stable annual average, with **windspeeds** typically ranging from 26 to 30 kilometres per hour (kph) across all

seasons. However, this apparent stability is accompanied by significant variability, as evidenced by the large error bars that extend from approximately 22 to 30 kph. This wide range reflects considerable fluctuations in windspeeds both within and between seasons. The trend suggests that, while the overall average remains consistent, actual wind conditions can be unpredictable and variable throughout the year. This combination of a stable average with high variability highlights the complex and dynamic nature of wind patterns in the area.

5.4.2 Indoor environmental monitoring report: Inside compartment

School 1 (**Figure 5.5**), located on Auckland's North Shore, initially had three IEMs installed on August 29th, 2022. After acquiring more IEMs, an additional three IEMs were installed on August 11th, 2023, which provided coverage to all classrooms in School 1 until June 21st, 2024.

FIGURE 5.5: School 1 IEQ Classroom Layout



This section presents an overview of the key IEQ measurements obtained from six classrooms in School S1, with data collected throughout multiple seasons (as illustrated in **Table 5.19**).

Analysing **temperature** data across seasons reveals several key patterns and trends. Winter and spring typically exhibit temperatures below the recommended range, while summer and autumn generally fare better, falling within or slightly above the desired range. In particular, S1-4 and S1-6 consistently show higher temperatures than in other areas, regardless of the season. Interestingly, there is a discernible improvement in meeting the temperature criteria from 2022 to 2024, suggesting that possible interventions may have been implemented during this period.

However, further adjustments are necessary to comply fully with the WHO criteria. The heating systems in most rooms would need to be improved for winter and spring to increase the temperatures to the recommended range. In contrast, some rooms, particularly S1-4 and S1-6, would benefit from enhanced cooling capabilities during summer and autumn to prevent overheating. These observations highlight the importance of targeted climate control strategies to maintain optimal comfort levels throughout the year while meeting established health standards.

An analysis of **RH** data reveals several key observations about the levels in different rooms and seasons. S1-4 and S1-6 consistently comply with ASHRAE criteria throughout all measured seasons, demonstrating effective humidity control. S1-5 also performs well, meeting the requirements in most instances, with only a minor exceedance observed in winter 2024. In contrast, S1-1, S1-2, and S1-3 frequently exceed the upper limit of 60% RH, particularly during the spring and summer seasons, indicating potential issues with humidity management in these spaces. A seasonal pattern emerges, with winter seasons generally exhibiting lower RH levels that often fall within the recommended range. In contrast, the summer and spring seasons tend to have higher levels of RH, often exceeding the upper limit 60%. These observations suggest that while some rooms maintain consistent humidity control throughout the year, others struggle to manage higher moisture levels during warmer seasons, highlighting areas for potential improvement in environmental management strategies.

TABLE 5.19: *Temperature, RH and CO₂ Mean [SD] for North Shore Auckland School (S1) (09:00 - 15:00 School Days Only)*

Room	Season	Temp (°C)	RH (%)	CO ₂ (ppm)
1	Winter '22	15.5 [4.7]	53 [2]	442 [15]
1	Spring '22	15.6 [3.2]	61 [10]	435 [23]
1	Summer '23	22.4 [1.4]	68 [10]	423 [17]
1	Autumn '23	17.5 [1.4]	69 [8]	432 [33]
1	Winter '23	14.7 [1.2]	60 [8]	448 [24]
1	Spring '23	18.2 [1.7]	62 [7]	423 [21]
1	Summer '24	20.3 [1.2]	65 [9]	421 [16]
1	Autumn '24	22.6 [3.7]	56 [8]	446 [69]
2	Winter '22	15.4 [4.7]	53 [2]	437 [15]
2	Spring '22	16.6 [3.2]	60 [9]	433 [23]
2	Summer '23	21.5 [1.2]	62 [6]	455 [20]
2	Autumn '23	20.6 [1.7]	60 [6]	440 [30]
2	Winter '23	15.4 [1.6]	60 [4]	511 [62]
2	Spring '23	17.8 [1.9]	64 [5]	445 [21]
2	Summer '24	20.4 [1.3]	64 [9]	417 [19]
2	Autumn '24	24.8 [1.7]	63 [16]	438 [25]
3	Winter '22	15.6 [2.7]	55 [1]	440 [15]
3	Spring '22	17.0 [2.5]	61 [9]	431 [24]
3	Summer '23	22.5 [1.4]	67 [9]	422 [22]
3	Autumn '23	20.6 [1.7]	60 [6]	440 [30]
3	Winter '23	17.2 [3.3]	57 [5]	479 [47]
3	Spring '23	18.2 [1.6]	62 [6]	442 [37]
3	Summer '24	22.9 [1.3]	59 [7]	450 [35]
3	Autumn '24	19.9 [1.2]	58 [5]	429 [25]
3	Winter '24	18.2 [1.0]	62 [5]	426 [22]
4	Summer '24	27.2 [1.5]	51 [6]	478 [87]
4	Autumn '24	24.1 [2.0]	53 [8]	528 [119]
4	Winter '24	22.5 [1.4]	56 [5]	649 [260]
5	Spring '23	18.1 [2.4]	57 [1]	504 [41]
5	Summer '24	23.5 [1.1]	55 [5]	436 [25]
5	Autumn '24	19.5 [2.4]	58 [6]	430 [25]
5	Winter '24	17.5 [1.0]	63 [4]	424 [25]
6	Summer '24	29.7 [1.4]	47 [2]	490 [40]
6	Autumn '24	26.2 [3.4]	48 [11]	484 [123]
6	Winter '24	23.7 [3.9]	52 [10]	566 [243]

All recorded **CO₂ concentrations** are well below the 1000 ppm threshold, the highest recorded mean value being 649 ppm in Room 4 during winter 2024, which is still significantly below the limit. There is a slight tendency for CO₂ levels to be higher in

the winter months, particularly noticeable in S1-4 and S1-6. In contrast, the summer months generally show lower CO₂ concentrations in all rooms.

Temperature

Table 5.20 illustrates the percentage of time the classrooms in the Auckland school fell within specific temperature ranges in different seasons.

TABLE 5.20: *Temperature Cuts for North Shore Auckland School (09:00 - 15:00 School Days Only)*

School	Room	Season	Below 16	[16-18[	[18-24[	[24-28[	Above 28
S1	1	Winter '22	77%	22%			1%
		Spring '22	34%	46%	18%		2%
		Summer '23			90%	10%	
		Autumn '23	14%	23%	50%	13%	
		Winter '23	68%	26%	6%		
		Spring '23	3%	40%	55%		2%
		Summer '24			99%	1%	
		Autumn '24	3%	8%	52%	30%	7%
S1	2	Winter '22	80%	19%			1%
		Spring '22		9%	90%	1%	
		Summer '23			86%	14%	
		Autumn '23		8%	89%	3%	
		Winter '23	61%	33%	6%		
		Spring '23	9%	48%	41%		2%
		Summer '24			99%	1%	
		Autumn '24			46%	51%	3%
S1	3	Winter '22	70%	30%			
		Spring '22	28%	48%	24%		
		Summer '23			86%	13%	1%
		Autumn '23		8%	89%	3%	
		Winter '23	48%	28%	19%	5%	
		Spring '23	3%	37%	59%		1%
		Summer '24			53%	46%	1%
		Autumn '24		3%	30%	67%	
S1	4	Winter '24		4%	46%	50%	
		Summer '24			26%	63%	11%
		Autumn '24		1%	45%	52%	2%
S1	5	Winter '24			81%	19%	
		Summer '24			68%	32%	
		Autumn '24	7%	21%	65%	7%	
S1	6	Winter '24	9%	58%	33%		
		Summer '24				16%	84%
		Autumn '24		2%	22%	53%	23%
		Winter '24		3%	62%	26%	9%

Temperature variations across seasons and rooms show diverse patterns (**Table 5.20**):

- **Winter:** Most areas fall below 18 °C, with exceptions in S1-3 (18.2 °C), S1-4 (22.5 °C), and S1-6 (23.7 °C) during winter 2024.

- **Spring:** Temperatures generally remain below 18 °C, with slight exceptions in S1-1 (18.2 °C), S1-3 (18.2 °C), and S1-5 (18.1 °C) during spring 2023.
- **Summer:** Most areas maintain 18-24 °C, except S1-4 (27.3 °C) and S1-6 (29.7 °C) in Summer 2024, exceeding the upper limit.
- **Autumn:** Generally within the recommended range, with exceptions in autumn 2023 (S1-1 at 17.5 °C) and autumn 2024 (S1-2 at 24.8 °C and S1-6 at 26.1 °C).

Analysing the temperatures with WHO recommendations, most classrooms maintained optimal temperatures during summer but struggled in winter, highlighting the need for better heating solutions.

Relative Humidity

Table 5.21 presents data on the percentage of time the classrooms in the Auckland school maintain specific levels of RH in different seasons.

Some rooms (S1-4, S1-5, and S1-6) meet the ASHRAE criteria for RH, while others (S1-1, S1-2, and S1-3) frequently exceed the upper limit, especially in warmer seasons. Implementing dehumidification measures in these rooms could help bring the RH levels within the recommended range of 40% to 60%.

It should be noted that, while numerous readings exceed 60% RH, these levels are not typically considered significantly problematic in most cases. However, particular attention should be paid to readings that exceed 70% RH, as these require careful management. Persistent high humidity, especially above 70% RH, creates conditions that encourage mould growth. This fungal proliferation can not only compromise IAQ but also pose health risks to occupants (Menneer et al., 2022; Nielsen et al., 2004).

TABLE 5.21: RH Cuts for North Shore Auckland School (09:00 - 15:00 School Days Only)

School	Room	Season	Below 40	[40-60[	[60-70[	Above 70
S1	1	Winter '22		99%		1%
		Spring '22		32%	44%	24%
		Summer '23	-	29%	37%	34%
		Autumn '23	-	8%	55%	37%
		Winter '23	-	24%	43%	33%
		Spring '23		49%	30%	21%
		Summer '24		31%	44%	25%
		Autumn '24	2%	65%	25%	8%
S1	2	Winter '22	-	99%	-	1%
		Spring '22		32%	46%	22%
		Summer '23	-	34%	40%	26%
		Autumn '23		52%	40%	8%
		Winter '23		47%	53%	
		Spring '23		57%	43%	
		Summer '24		42%	51%	7%
		Autumn '24		54%		46%
S1	3	Winter '22	-	85%	15%	
		Spring '22		29%	45%	26%
		Summer '23	-	50%	43%	7%
		Autumn '23		53%	40%	7%
		Winter '23		63%	36%	1%
		Spring '23	-	43%	42%	15%
		Summer '24	1%	82%	10%	7%
		Autumn '24	3%	63%	24%	10%
S1	4	Winter '24	-	39%	52%	9%
		Summer '24	1%	89%	8%	2%
		Autumn '24	4%	74%	17%	5%
S1	5	Winter '24	-	75%	22%	3%
		Summer '24	-	85%	9%	6%
		Autumn '24	-	58%	34%	8%
S1	6	Winter '24	-	24%	67%	9%
		Summer '24	-	100%	-	-
		Autumn '24	20%	64%	10%	6%
		Winter '24	9%	69%	14%	8%

Carbon dioxide

NZMoE updated its classroom guidelines to manage IEQ and TC, responding to new health concerns such as the COVID-19 pandemic. These changes reflect a growing

emphasis on air quality and its potential impact on health, particularly in the context of respiratory viruses.

Before the pandemic, the 2017 guideline recommended maintaining CO₂ levels below 1000 ppm for acceptable IAQ. However, the updated MoE guidelines now stress the importance of keeping CO₂ levels below 800 ppm. If levels remain at or above this threshold for an hour or more, immediate action is advised (Fullbrook et al., 2022).

Although Clause G4 of the NZ Building Code and the NZS 4303:1990 standard remain unchanged, the MoE's revised school ventilation guidance demonstrates an increased focus on air quality. This shift highlights the critical role of proper ventilation in creating a safe and healthy learning environment for students and staff (Ministry of Education, 2023).

To facilitate comparison with pre-COVID-19 studies, this section will utilise both criteria for analysis.

Table 5.22 presents data on the percentage of time classrooms in the Auckland school maintain CO₂ concentrations in classrooms in Auckland within specific ranges during different seasons. It presents the findings of how each room performs with the NZS 4303:1990 standard and the original NZ MoE DQLS 2017 guidelines (Ministry of Education, 2017; Standards New Zealand, 1990a).

TABLE 5.22: CO₂ Cuts for North Shore Auckland School (Pre-COVID-19 Scale) (09:00 - 15:00 School Days Only)

School	Room	Season	[400-800[	[800-1000[	[1000-1500[	[1500-2000[	[2000-3000[	[3000-5000[
S1	1	Winter '22	100%					
		Spring '22	100%					
		Summer '23	100%					
		Autumn '23	100%					
		Winter '23	100%					
		Spring '23	100%					
		Summer '24	98%	1%	1%			
		Autumn '24	98%	1%	1%			
		Winter '24	98%	1%	1%			
S1	2	Winter '22	100%					
		Spring '22	100%					
		Summer '23	100%					
		Autumn '23	100%					
		Winter '23	100%					
		Spring '23	100%					
		Summer '24	98%	1%	1%			
		Autumn '24	98%	1%	1%			
		Winter '24	98%	1%	1%			
S1	3	Winter '22	100%					
		Spring '22	100%					
		Summer '23	100%					
		Autumn '23	100%					
		Winter '23	100%					
		Spring '23	100%					
		Summer '24	98%	1%	1%			
		Autumn '24	98%	1%	1%			
		Winter '24	98%	1%	1%			
S1	4	Summer '24		99%	1%			
		Autumn '24	95%	3%	2%			
		Winter '24	86%	4%	7%	2%		
S1	5	Summer '24		100%				
		Autumn '24		100%				
		Winter '24		100%				
S1	6	Summer '24	99%			1%		
		Autumn '24	92%	3%	4%	1%		
		Winter '24	90%	4%	4%	3%		

The classrooms in school S1 (Table 5.22) generally meet the NZ Standard and MoE guidelines for CO₂ levels. Most rooms consistently maintain CO₂ concentrations below the 1000 ppm threshold, with only minor short-duration deviations. Significantly, none of the rooms exceed the 1500 ppm level, ensuring that the occupants are not exposed to potentially harmful CO₂ concentrations. Some rooms, particularly S1-4 and S1-6, show more significant deviations during winter 2024 and autumn 2024; CO₂ levels are generally well below 800 ppm most of the time. This suggests that daily average CO₂ levels remain within acceptable limits, even accounting for short-term spikes. In general, classrooms comply with established

guidelines, providing a healthy indoor environment for students and staff.

For CO₂ levels, S1-1, S1-2, S1-3 and S1-5 performed consistently well **Table 5.22**, while S1-6 exhibited concerning trends, particularly in autumn and winter, possibly indicating ventilation problems.

In light of the evolving understanding of IAQ and its impact on health and learning, particularly in the context of the COVID-19 pandemic, it is crucial to re-assess classroom environments with updated ventilation criteria. The recent revision has tightened these requirements. The current MoE guidelines emphasise the maintenance of CO₂ levels well below the 1000 ppm threshold, explicitly aiming for levels below 800 ppm (Ministry of Education, 2023). This shift reflects a more proactive approach to ensure optimal air quality in educational settings. In this review (**Table 5.23**), we will examine how classrooms now measure up to these revised criteria.

The analysis of classroom CO₂ levels reveals varying degrees of compliance with the updated MoE guidelines (**Table 5.23**). S1-1, S1-2, S1-3, and S1-5 demonstrate overall high compliance, with only minor exceptions occurring primarily from summer 2024 to winter 2024. These rooms generally maintain CO₂ levels below the recommended 800 ppm threshold, indicating good ventilation practices. However, S1-4 and S1-6 show moderate to low compliance, particularly during specific seasons. S1-4 exhibits significant deviations, especially in winter 2024, where CO₂ levels frequently exceed the 800 ppm threshold, necessitating immediate action to improve ventilation and air quality. Similarly, S1-6 shows moderate deviations in autumn 2024 and winter 2024, with sustained higher CO₂ levels, indicating the need for improved ventilation strategies. These findings highlight the importance of targeted interventions and continuous monitoring to ensure that all classrooms consistently meet the updated MoE guidelines for optimal IAQ.

TABLE 5.23: CO₂ Cuts for North Shore Auckland School (Post COVID-19 Scale) (09:00 - 15:00 School Days Only)

School	Room	Season	Below 800	[800-1250[	[1250-2000[	Over 2000
S1	1	Winter '22	100%			
		Spring '22	100%			
		Summer '23	100%			
		Autumn '23	100%			
		Winter '23	100%			
		Spring '23	100%			
		Summer '24	98%	1.00%	1.00%	
		Autumn '24	98%	1.00%	1.00%	
		Winter '24	98%	1.00%	1.00%	
S1	2	Winter '22	100%			
		Spring '22	100%			
		Summer '23	100%			
		Autumn '23	100%			
		Winter '23	100%			
		Spring '23	100%			
		Summer '24	98%	1.00%	1.00%	
		Autumn '24	98%	1.00%	1.00%	
		Winter '24	98%	1.00%	1.00%	
S1	3	Winter '22	100%			
		Spring '22	100%			
		Summer '23	100%			
		Autumn '23	100%			
		Winter '23	100%			
		Spring '23	100%			
		Summer '24	98%	1.00%	1.00%	
		Autumn '24	98%	1.00%	1.00%	
		Winter '24	98%	1.00%	1.00%	
S1	4	Summer '24		99.00%	1.00%	
		Autumn '24	95.00%	3.00%	2.00%	
		Winter '24	86.00%	4.00%	9.00%	
S1	5	Summer '24		100.00%		
		Autumn '24		100.00%		
		Winter '24		100.00%		
S1	6	Summer '24	99.00%		1.00%	
		Autumn '24	92.00%	7.00%	1.00%	
		Winter '24	90.00%	8.00%	3.00%	

The increase in CO₂ levels observed in S1-1, S1-2 and S1-3 is probably due to the TC&V experiments. The typical window settings of the classrooms were adjusted and an industrial heater was used to regulate the classroom TC for cognitive tests. These adjustments likely influenced the CO₂ levels, as manipulating the window settings can change ventilation rates, and the use of heaters can affect air circulation. Together, these factors may contribute to the observed variations in CO₂ levels during experiments.

Overall, while most classrooms in School S1 meet or exceed ventilation standards, targeted improvements are necessary for S1-4 and S1-6 to maintain consistent air quality standards throughout the year.

Classroom comparison and seasonal adjustments

- Most comfortable in summer: Rooms S1-1 and S1-2 performed the best in maintaining optimal temperatures.
- Winter challenges: Rooms S1-2 and S1-3 frequently fell below the recommended temperature range, indicating possible discomfort.
- Consistent performance: Rooms S1-1 and S1-4 showed resilience in maintaining optimal temperatures in different seasons, highlighting efficient temperature control mechanisms.
- Action needed: Specifically targeted improvements are needed, particularly in the winter months, to ensure that heating solutions are adequate and temperatures remain within the ideal range (18-24 °C). In addition, monitoring and adjusting ventilation practices can address the higher CO₂ levels observed during colder periods.

In summary, the climate in School S1 generally provided a comfortable year-round experience for students, although Rooms S1-2 and S1-3 sometimes had too-low winter temperatures. CO₂ levels in most rooms remained below the 1000 ppm guideline, notably improving in summer with better ventilation practices. WHO suggests 18-24 °C for student comfort, which most rooms achieved in summer but struggled with in winter, indicating the need for better heating. RH met primarily the ASHRAE recommendations except in spring and autumn. The NZ MoE updated its guidelines to maintain CO₂ levels below 800 ppm due to concerns about COVID-19 (Ministry of Education, 2023), highlighting improved air quality. The room-specific evaluation revealed good performance generally, but Room 6 showed high CO₂ levels in autumn and winter, indicating that ventilation problems need to be addressed. The TC&V experiments with window adjustments and heaters likely influenced CO₂ variations. Targeted ventilation improvements are recommended for Rooms S1-4 and S1-6 to adhere to air quality standards consistently.

5.5 General discussion

5.5.1 Key temperature observations from Hawkes' Bay, Christchurch, and Dunedin

Based on the temperature information provided, it is challenging to definitively state which region performs better overall, as each region (Hawkes' Bay, Christchurch, and Dunedin) shows varying performance in different classrooms and seasons. However, we can make some observations:

1. Hawkes' Bay: Only one classroom met the WHO recommended temperature range (18-24 °C) during occupied hours in spring and autumn. Some classrooms experienced temperatures outside the comfort zone, especially in winter and summer.
2. Christchurch
 - C1-1 performed consistently well throughout all seasons.
 - C2-3 excelled in spring.
 - C3-2 demonstrated good performance over multiple seasons.
 - C4-1 was noted as the classroom that performed consistently well throughout all seasons.
3. Dunedin
 - D1-1 performed exceptionally well in maintaining optimal temperatures in various seasons.
 - D2-4 was highlighted as the best performing class overall for maintaining optimal learning temperatures.
 - D3-3 was noted as the best performing classroom in terms of maintaining optimal temperatures for learning throughout the year.

Based on this information, **Christchurch and Dunedin perform better than Hawkes' Bay in maintaining optimal classroom temperatures.** Both Christchurch and Dunedin have multiple classrooms that perform consistently well in all seasons.

Determining a clear winner between Christchurch and Dunedin is difficult as both regions have top performers. Christchurch's C4-1 and Dunedin's D3-3 demonstrate

consistent performance across all seasons.

However, given that multiple classrooms in Dunedin (D1-1, D2-4, D3-3) are specifically highlighted for their excellent performance across seasons, Dunedin might have a slight edge overall. *It is important to note that this conclusion is based on limited information and may not represent the entire picture for each region.* A more comprehensive analysis would be needed to make a definitive statement on which region performs best overall.

5.5.2 Key relative humidity observations from Hawkes' Bay, Christchurch, and Dunedin

Based on the analysis provided, it is challenging to definitively state which region performs better overall, as performance varies between different schools, classrooms, and seasons within each region.

1. Hawkes' Bay

- Generally good performance in spring and autumn
- Some classrooms struggle in winter
- Varied performance across different schools and classrooms

2. Christchurch

- Some classrooms show excellent performance (e.g., C1-1, C2-3, C3-3, C4-1)
- Spring often emerges as the best-performing season
- Significant variations between classrooms and schools

3. Dunedin

- Generally good performance across seasons, with autumn standing out as the best season
- Some classrooms (e.g., D1-2, D2-4, D3-3) show consistently good performance
- Winter performance is mixed across different schools

It is difficult to declare a clear "winner" among these regions. Each region has its strengths and weaknesses:

- Hawkes' Bay performs well in spring and autumn but struggles in winter.
- Christchurch has some excellent classrooms with excellent performance, particularly in spring.
- Dunedin demonstrates good overall performance, especially in autumn, with some classrooms maintaining consistent RH levels throughout the year.

Dunedin might have a slight edge if asked to choose due to its consistent performance across seasons and the fact that autumn is a particularly strong season to maintain optimal RH levels. However, this conclusion should be taken with caution, as performance varies significantly within each region and a more comprehensive statistical analysis would be needed to make a definitive comparison.

5.5.3 Key CO₂ observations from Hawkes' Bay, Christchurch, and Dunedin

Based on the information provided, it is difficult to make a definitive statement about which region performs better overall, as the data is presented differently for each region, and the performance varies between seasons and individual classrooms.

1. Hawkes' Bay

- H1 Room 1 performs better in spring and autumn
- H1 Room 2 performs better in winter
- Overall, H1 Room 1 seems to perform better across multiple seasons

2. Christchurch

- Many classrooms frequently exceed recommended CO₂ limits
- Some classrooms (C4-3A and C4-3B) demonstrate consistently good air quality across all seasons
- Spring appears to be the season with the best overall performance
- Winter is often the most problematic season

3. Dunedin

- D1-3A (and D1-3B) performs best in maintaining optimal CO₂ levels

- D2-1 generally performs best in its school, especially in spring and summer
- D3-2A and 2B perform better than other rooms in their school
- Summer appears to be the best season overall for maintaining optimal CO₂ levels in School D3

Given this information, it is challenging to determine which region performs better overall. Each region has some well-performing classrooms and some that struggle to maintain optimal CO₂ levels. Performance also varies significantly over seasons.

If forced to choose, Dunedin might have a slight edge due to the consistent performance of some classrooms (like D1-3A and D3-2A/B) and the generally good performance during summer. However, this conclusion should be taken with caution, as data presentation and analysis methods differ between regions, making direct comparisons difficult.

5.5.4 Implications for TC&V strategies

The findings of these deployments indicate that primary schools in NZ face significant challenges in maintaining TC and adequate ventilation, particularly during the extreme seasons.

- **Winter challenges:** Winter is a problematic season for maintaining TC in all deployments, and classrooms often experience temperatures below the recommended range of 16-20 ° C. Poor heating systems in older buildings contribute to this problem. For example, in Christchurch and Dunedin, inadequate heating resulted in uncomfortable and potentially unhealthy student environments.
- **Summer challenges:** Overheating during summer was prevalent, particularly in Classrooms B and some Dunedin classrooms. Although opening windows can alleviate high CO₂ levels, it may not be sufficient when external temperatures rise, highlighting the need for more integrated HVAC systems to moderate temperature and air quality.

The findings of this study are supported by international studies, such as those of Wargocki and Wyon (2006, 2007a, 2007b), which consistently show that maintaining optimal temperature ranges is crucial for student performance, with deviations resulting in negative impacts on cognitive functions. In NZ-specific contexts, Wang

(2020) identified inconsistent temperature controls in NZ classrooms, with many classrooms recording temperatures either below or above recommended levels. This study supports these findings, indicating that TC issues are a global phenomenon and represent a significant concern in NZ classrooms.

The data of this study reveal concerning trends, particularly in winter, where S1-3 at 15.6 °C and S1-2 at 15.4 °C fall below the ideal temperature range of 18-24 °C for classrooms. These findings highlight the need for improved heating solutions to maintain optimal cognitive performance and student comfort during the colder months, ensuring that indoor temperatures are aligned with established standards for effective learning environments. Historical studies by Pepler and Warner (1968) and Holmberg and Wyon (1969) highlighted the impact of thermal conditions on classroom performance, with thermally controlled environments yielding better results and higher temperatures leading to decreased reading comprehension, especially in the afternoon due to fatigue.

5.5.5 CO₂ levels and ventilation effectiveness

CO₂ measurements, used as a proxy of ventilation effectiveness, revealed critical insights into the IEQ challenges faced during different seasons.

- **Winter CO₂ levels:** Winter saw significantly high CO₂ levels across several classrooms, indicating poor ventilation. For example, CO₂ concentrations regularly exceeded 1000 ppm in classrooms in Christchurch and Hawke's Bay. The high occupancy and inadequate ventilation systems contributed to these elevated levels, negatively impacting students' cognitive functions and overall well-being. Improve ventilation in S1-4 and S1-6 during winter 2024 and autumn 2024 to reduce CO₂ levels consistently below 800 ppm.
- **Spring and autumn CO₂ levels:** Generally, spring and autumn reported better adherence to recommended CO₂ levels, suggesting that moderate external temperatures facilitate better NV. This seasonal variability highlights the potential benefit of passive ventilation strategies when outdoor conditions are favourable.
- **Summer CO₂ levels:** The lowest CO₂ levels were often recorded in summer, albeit with overheating issues. This paradox highlights a trade-off between TC

and air quality, suggesting that while open windows improve ventilation, they might simultaneously lead to excessive heat ingress.

The observed seasonal and daily variations align with the existing literature on TC and IEQ in schools. Studies highlight high CO₂ levels due to occupancy and insufficient ventilation (Chatzidiakou et al., 2015; Smedje and Norbäck, 2000), along with challenges in temperature regulation (Bakó-Biró et al., 2007). High CO₂ levels impair cognitive function and student health (Fromme et al., 2008; Gaihre et al., 2014; Wargocki, 2022). Current data show 58% of CO₂ readings below 1000 ppm, but seven averages exceeded 1200 ppm, particularly in winter. Summer performance improved with open windows.

International studies (Fromme et al., 2008; Gaihre et al., 2014; Y. Zhang et al., 2016; Zapata-Lancaster et al., 2023) and NZ-specific research (McIntosh, 2011; National Institute of Water and Atmospheric Research, 2022) consistently report CO₂ levels exceeding recommended thresholds, especially during the colder months. This study corroborates these findings, emphasising prevalent elevated CO₂ levels due to insufficient ventilation in primary school classrooms.

5.5.6 Analysis of IAQ deviations pre- and post-COVID in NZ naturally ventilated classrooms

While most of the rooms examined maintained commendable air quality within acceptable parameters, episodes of CO₂ level gains, particularly in S1-4 and S1-6, were notable. These findings highlight potential inadequacies in the NV capabilities of buildings, necessitating a reassessment and, possibly, enhancement of air quality management strategies to cope with varying occupancy and activity levels. The updated ventilation guidelines stress the importance of ensuring that CO₂ concentrations remain below the 800 ppm target, and proactive interventions are recommended should levels persistently exceed this limit for durations longer than an hour (Ministry of Education, 2023).

Highlighting these findings is that classrooms do not have mechanical ventilation systems and are entirely dependent on NV methods. This reliance on changes in natural airflow exposes the limitations inherent in such systems, particularly in their dependence on external environmental fluctuations such as temperature, wind

patterns, and the structural placement of ventilation openings.

The imperative for judiciously designed NV becomes paramount in environments devoid of mechanical ventilation. Openings such as windows and doors must be strategically placed and dimensioned to facilitate optimal natural air flow. To further improve air quality under the NV regimes, especially during periods of increased room occupancy or increased indoor activities, it is advisable to encourage the inhabitants to participate in classroom airing (Atkinson et al., 2009).

The disparities in CO₂ concentration across classrooms suggest that relying on NV without careful design and management can lead to suboptimal IAQ (Atkinson et al., 2009). This poses a health risk due to potential indoor air pollution and can impact cognitive functions, particularly in educational settings where concentration and performance are essential (Fullbrook et al., 2022). The recorded deviations and elevated CO₂ concentrations, particularly highlighted in S1-4 and S1-6, accentuate the limitations of NV in specific scenarios. In such circumstances, contemplation of supplemental ventilation strategies might be warranted, potentially through the introduction of operable windows, strategic placement of ventilation ducts, supplementation of air movement with fans, or the incorporation of air purifying or filtration mechanisms. This is assuming that the behaviour of the teacher has not changed. The data collected do not explicitly address whether teachers are reverting to their original behaviour state. However, it shows that CO₂ levels in some classrooms have increased since the pandemic, suggesting that some teachers may be less vigilant in maintaining good ventilation practices.

For example, S1-4 showed a significant increase in CO₂ levels during winter 2024, with 86% of the time spent below 800 ppm, 4% in the 800-1250 ppm range, and 9% in the 1250-2000 ppm range. Similarly, S1-6 showed a decrease in compliance during autumn 2024, with 92% of the time spent below 800 ppm, 7% in the 800-1250 ppm range, and 1% in the 1250-2000 ppm range.

Although these increases in CO₂ levels could be due to various factors, such as changes in occupancy or outdoor conditions, they could also suggest that some teachers may be less focused on maintaining good ventilation practices. However, drawing definitive conclusions about teacher behaviour without additional data or context is difficult.

Although not distinctly categorising classrooms into 'good' or 'bad' air quality based only on CO₂ levels, the data highlight the variability and suggest that underlying factors could contribute to these inconsistencies. It may be that specific classrooms have a more advantageous position in the building for NV. In contrast, others may be disadvantaged due to their location, occupancy levels, number of openings, or behavioural patterns of teachers.

To adequately address these issues, it is important to consider a holistic approach that does not rely solely on CO₂ measurements. Some additional steps that could be taken are the following:

1. **Comprehensive air quality assessment:** In addition to temperature, RH and CO₂, other parameters such as VOCs and PM could also be monitored to obtain a complete picture of air quality (Ministry for the Environment, 2009).
2. **Customized ventilation strategies:** Ventilation requirements may differ according to classroom usage, the number of occupants, and the specific activities that are being carried out. Strategies should be flexible and adaptable to these varying needs (Atkinson et al., 2009; Persily, 2015).
3. **Occupancy scheduling:** Staggering class schedules or reducing the number of people in a classroom at any given time can lessen the CO₂ load and other pollutants (Batterman, 2017; Luther et al., 2018).
4. **Investment in smart controls:** Integrating sensors and automation systems can help in dynamically adjusting ventilation based on real-time IAQ readings (Chinnakannan, 2024; Mistry, 2023).
5. **Community engagement:** Engaging the school community in understanding the importance of air quality and including them in solutions can lead to more effective results (Ward et al., 2022).
6. **Policy and guidelines:** Establishing clear policies and guidelines for IAQ that align with the latest research and best practices can help ensure consistent application in all classrooms.

By taking these initiatives, schools can work towards providing a consistently healthy and supportive environment for all students and staff, tailored to each

classroom space's unique conditions and uses.

In summary, the observed inconsistencies in CO₂ levels within specific classrooms point to the need to plan and manage the present NV systems. These measures are imperative to secure and maintain IEQ that fulfils the students' health and cognitive performance standards.

5.5.7 Seasonal challenges and opportunities for natural ventilation in NZ primary school classrooms

Temperature and heating:

NZ MoE's NV preference presents seasonal challenges. Winter requires balancing fresh air intake with heat conservation, while summer demands effective cooling strategies. Stable summer temperatures reduce airing needs, but extreme heat can discourage window opening. The complexity of the year-round implementation requires adaptive approaches that balance TC, energy efficiency, and IAQ. Achieving >800 ppm CO₂ targets requires strategies that address seasonal variations while maintaining healthy learning environments (Arya et al., 2024; Sutherland et al., 2022; Y. Wang et al., 2019).

Relative humidity and comfort:

Seasonal RH variations challenge NV in NZ classrooms. winter/autumn's higher RH with cooler temperatures necessitates frequent airing to manage moisture and prevent mould, balancing air quality and TC. Spring/summer's lower, variable RH offers effective NV opportunities, but cooling needs may limit airing. Year-round implementation requires nuanced and adaptive approaches to changing weather conditions, maintaining optimal IEQ and comfort. Balancing ventilation with TC and moisture management remains crucial throughout the seasons (Bengtsson et al., 2007; Boulic et al., 2016; Ministry of Education, 2023).

Rainfall and moisture management:

Rainfall patterns and moisture management challenge year-round NV in NZ classrooms. Winter/autumn's moderate rainfall increases indoor humidity, complicating ventilation efforts due to warmth preservation and rain exclusion

needs. Spring/summer's fluctuating rainfall disrupts airing with sudden showers, risking water ingress. Outdoor humidity impacts ventilation effectiveness even in drier periods. Seasonal variability necessitates flexible; adaptive ventilation approaches responding to weather changes while maintaining comfortable, healthy indoor environments (Bengtsson et al., 2007).

Windspeed and ventilation:

NZ's annual wind variability (22-30 kph) presents opportunities and challenges for classroom NV. Higher winds enhance air exchange and IEQ, but risk draughts and discomfort. Lower winds require alternative circulation methods. Unpredictable conditions require adaptable and flexible ventilation systems with thoughtful window design/placement. Dynamic approaches to balance air quality, TC and occupant well-being in varying weather conditions are essential (Ackley_Longley_Chen_MacKenzie_Sutherland_Jermy_Phipps_Gronert_2022b; Ministry of Education, 2023; Sutherland et al., 2022).

5.6 Reflection on methodological strengths and limitations

Strengths:

1. **Comprehensive monitoring across seasons:** The year-long deployment of IEMs provided robust data in different climatic conditions, lending credence to the seasonal analysis of TC and ventilation challenges.
2. **Multi-regional study:** By encompassing diverse geographic locations such as Hawke's Bay, Christchurch, and Dunedin, the study accounted for regional climatic variations, offering a more representative picture of primary school conditions in NZ.
3. **Use of CO₂ as a proxy for ventilation:** This straightforward yet effective approach facilitated the assessment of ventilation adequacy without needing more complex and potentially costly direct measurements.

Limitations:

1. **Data gaps:** The missing data from Christchurch introduced some uncertainties into the findings. Future studies should strive for complete data collection to ensure the robustness of the results.
2. **Proxy measurements:** Although CO₂ levels are a reasonable proxy for ventilation, they do not capture the complete picture of IEQ, such as other pollutants or general airflow patterns.

5.7 Conclusions

This study has explored the intricate dynamics of TC and CO₂ levels, serving as a proxy for adequacy of ventilation in primary school classrooms in various regions of NZ. The findings reveal significant seasonal variability and regional disparities in maintaining optimal indoor environmental quality, emphasizing the need for tailored solutions to ensure healthy and comfortable learning environments.

5.7.1 Thermal comfort and seasonal variability

The analysis highlights the considerable challenges faced during winter and summer to maintain temperatures within the recommended ranges. Winter months often recorded suboptimal temperatures, indicating a pressing need for improved classroom heating solutions. In contrast, the summer months frequently presented overheating issues, particularly in NV classrooms, calling for improved cooling mechanisms to alleviate discomfort.

Regions like Christchurch and Dunedin generally performed better in maintaining optimal temperatures than Hawke's Bay, with certain classrooms demonstrating consistent performance across seasons. Despite this, no single region emerged as a clear overall winner, highlighting the localised nature of TC challenges.

5.7.2 Relative humidity management

RH levels showed notable seasonal patterns, with winter and autumn experiencing higher RH that often exceeded recommended thresholds, potentially leading to humidity-related problems such as mould growth. In contrast, spring and summer

presented lower and more variable RH levels, offering better opportunities for effective NV but necessitating careful moisture management.

Dunedin's classrooms displayed a slight edge in maintaining consistent RH levels across seasons, particularly in autumn, underscoring the need for adaptive strategies that account for seasonal fluctuations.

5.7.3 CO₂ levels and ventilation effectiveness

The CO₂ measurements revealed critical insights into ventilation effectiveness, with winter generally presenting the highest CO₂ levels due to reduced ventilation rates. Spring and autumn showed relatively better adherence to recommended CO₂ levels, indicating the benefits of passive ventilation during moderate external temperatures. Summer presented the lowest CO₂ levels, highlighting the trade-off between TC and air quality, since opening windows improved ventilation but potentially led to overheating.

Dunedin consistently demonstrated better performance in maintaining CO₂ levels within optimal ranges, particularly during summer, suggesting effective regional ventilation practices.

In general, this study provides a detailed benchmark for the levels of TC and CO₂ in various primary school classrooms in NZ, highlighting systemic challenges and opportunities for improvement. Schools can improve indoor environmental quality by adopting comprehensive and adaptive strategies tailored to seasonal and regional nuances, promoting better health, comfort, and academic performance for students and staff. Future research should build on these findings to develop more robust and targeted interventions that address the specific needs of different schools while considering the impacts of climate change on seasonal variability. Collaboration between researchers, educators, policy makers and the broader community will be essential to create effective and sustainable solutions to maintain optimal indoor environmental quality in educational settings. In doing so, we can ensure that all students learn in environments conducive to their well-being and academic success.

Chapter 6

FACTORS INFLUENCING WINDOW OPENING BEHAVIOUR

This chapter unfolds in four sections, each dedicated to exploring a different facet pertinent to the achievement of Aim 2. The journey begins with the **door and window questionnaire**, initially administered in Auckland (North Island) in 2015, setting a precedent for similar studies carried out in Christchurch Dunedin (South Island) in 2017 (Gully, 2015 Liaw, 2015) and again in Auckland (North Island) in 2024, carried out by the PI.

The narrative then progresses to **observational studies at School 1**. The final section addresses the **window and door sensor analysis**, presenting a dissection of the collated data and its relevance within the framework of the study's goals.

6.1 Questionnaire results and discussion

6.1.1 Response rate

Table 6.1 provides an overview of the distribution of the study questionnaire. The table shows the total number of questionnaires distributed to participants, the number of responses received, the number of invalid responses, and the response rate.

TABLE 6.1: *Questionnaire Distribution and Response Rate Summary*

	2015	2017	2024	Total
Circulated to	92	35	12	139
Returned	74	18	9	101
Invalid	n/a	2	n/a	2
Responses	74	16	9	99
Response rate	80%	51%	75%	

A total of **139** questionnaires were distributed among participants, resulting in an initial response of **101** completed surveys. Following exploratory data analysis, it was decided to exclude data from two participants, leading to a revised sample size of **n=99**. The reasons for exclusion included an incomplete questionnaire from one participant and misaligned responses with the research objectives of another, resulting in a final response rate of **71%**.

The disparity in response rates, with significantly higher figures of 80% and 75% observed in instances where face-to-face discussions were employed, can be attributed primarily to the personal and engaging nature of direct interactions. In-person conversations tend to evoke a greater sense of commitment and urgency, which can foster a higher level of responsiveness. The immediacy of the interaction encourages immediate feedback and often yields higher response rates as respondents are presented with the opportunity to react on the spot. In contrast, the lower response rate of 51% associated with email circulation highlights the challenges of digital communication. Despite the convenience of emails, they can easily be overlooked, ignored, or lost in an overflowing inbox. The lack of a personal touch and the deferred nature of the communication can contribute to a less compelling call to action, resulting in respondents being less prompt or less likely to engage altogether.

Although the PI's initial intention was to conduct analysis at the individual student level, this was precluded by the high-risk ethics committee's stipulations. The approved ethical framework required that all data be aggregated and maintained at the classroom level, thus restricting comparisons to between-classroom analyses and prohibiting any student-level investigation.

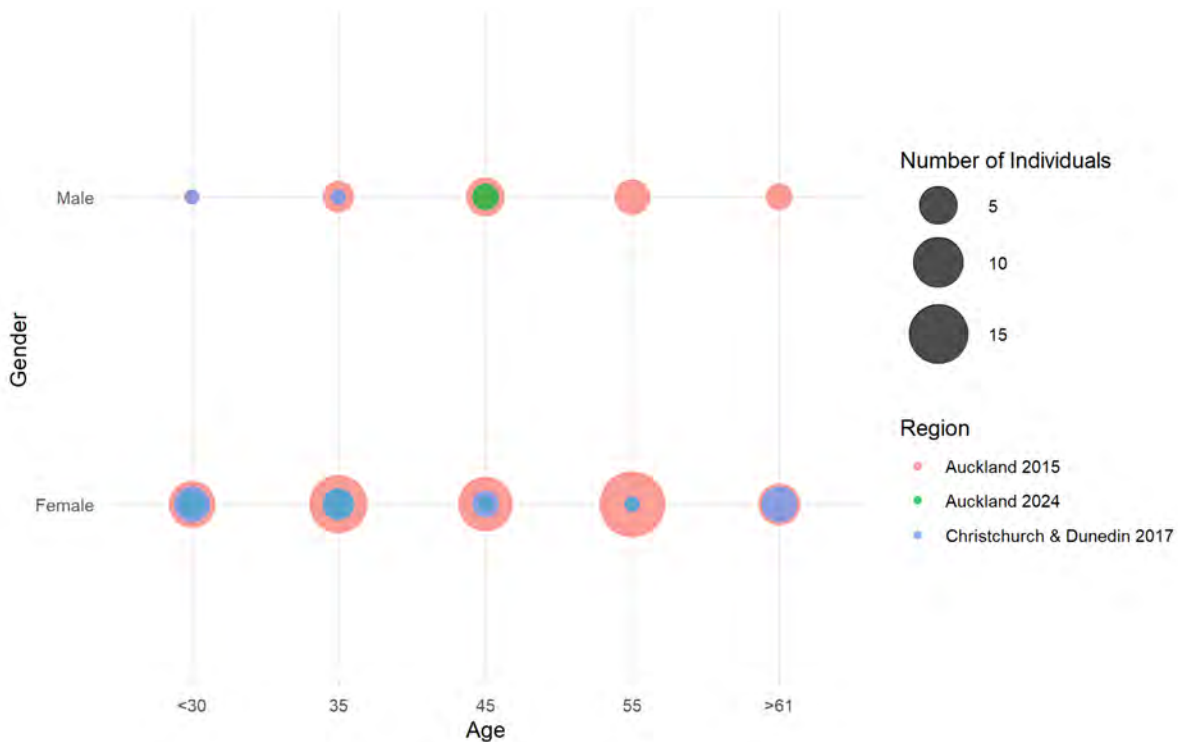
The PI considered analysing the data by year groups i.e. 2015, 2017 and 2024 or pre and post-COVID-19. While analysing data by year groups or pandemic groups might initially seem appealing, the limited sample size within each year group presents a significant obstacle to robust analysis.

Disaggregating the data further would reduce the statistical power and potentially lead to unreliable or misleading conclusions. The current aggregated approach, while acknowledging the potential developmental variation between the year groups, prioritises the overall validity and generalisability of the findings given the available data. A more granular analysis by year groups would be valuable in future research, contingent on obtaining a larger dataset that provides sufficient statistical power within each cohort. The same answer applies to analysing data by regions.

6.1.2 Demographic profiling

Figure 6.1 provides a comparative overview of the age and gender distribution of teachers in three different periods and regions. A significant majority, **81%**, were female, while **19%**, were male.

FIGURE 6.1: Age and Gender Distribution of Teachers by Region and Study Year



11% were under the **age of 30**, 19% were aged **between 30 and 39**, 23% fell into the **40 to 49 age bracket**, 31% were **between 50 and 59**, and the remaining 16% were **60 years or older**.

The broad age distribution of the respondents indicates diverse experience levels and generational perspectives. 70% of the respondents were older than 40 years. This suggests that the teacher population has a strong representation of individuals who are potentially quite experienced in their profession. Those between the ages of 30 and 49, considered mid-career, make up 42% of the respondents (19% for 30-39 and 23% for 40-49). The 16% of teachers above 60 represents a seasoned segment of the education workforce.

The study context (81% female) reflects NZ primary teacher demographics, especially at the primary level. MoE figures support the results: 85% primary and 65% secondary teachers are women (Statistics New Zealand, 2023). According to the International Teaching and Learning Survey conducted by the OECD, the average

age of teachers in NZ is 44 years, aligning with the OECD average. Furthermore, 35% of NZ teachers were found to be 50 years or older. The survey also revealed that 65% of NZ teachers are female, slightly below the OECD average of 68% (RNZ, 2019).

This is how this particular distribution could impact the study:

1. **TC&V preferences:** Research has suggested that TC preferences can vary between genders (Griefahn and Künemund, 2001; Haselsteiner, 2021; Indraganti and Humphreys, 2021; Karjalainen, 2007). Data might be skewed towards their comfort preferences if most of the participants are women. This is particularly relevant in teaching, where classroom conditions affect teacher performance and student outcomes. This could impact the results due to TC&V preferences.
2. **Occupant behaviour:** Women and men may have different habits or preferences when opening windows (de Dear et al., 2013; Hashiguchi et al., 2010; Maykot et al., 2022; Romero et al., 2023), which can affect ventilation and, consequently, TC&V. The female-dominated sample could mean that the findings reflect more on how female teachers might respond to TC&V challenges or control measures.
3. **Teacher and student well-being:** Since women occupy the field predominantly (Statistics New Zealand, 2023), policies based on study findings would mainly influence the work conditions and well-being of women teachers, which could have a greater impact on teaching efficacy and student performance.
4. **Educational environment:** Understanding the behaviours and preferences of the dominant gender in teaching staff could help design classrooms that cater to the teachers' comfort, creating an environment conducive to learning.
5. **Implications for facility management:** The results of such a sample could better inform facility managers and designers when considering building or renovating schools, ensuring that the indoor environmental controls align with the needs of the majority of the user group.

Figure 6.2 represents the Ages vs Teaching experience output.

FIGURE 6.2: Relationship between Age and Number of Years of Teaching Experience

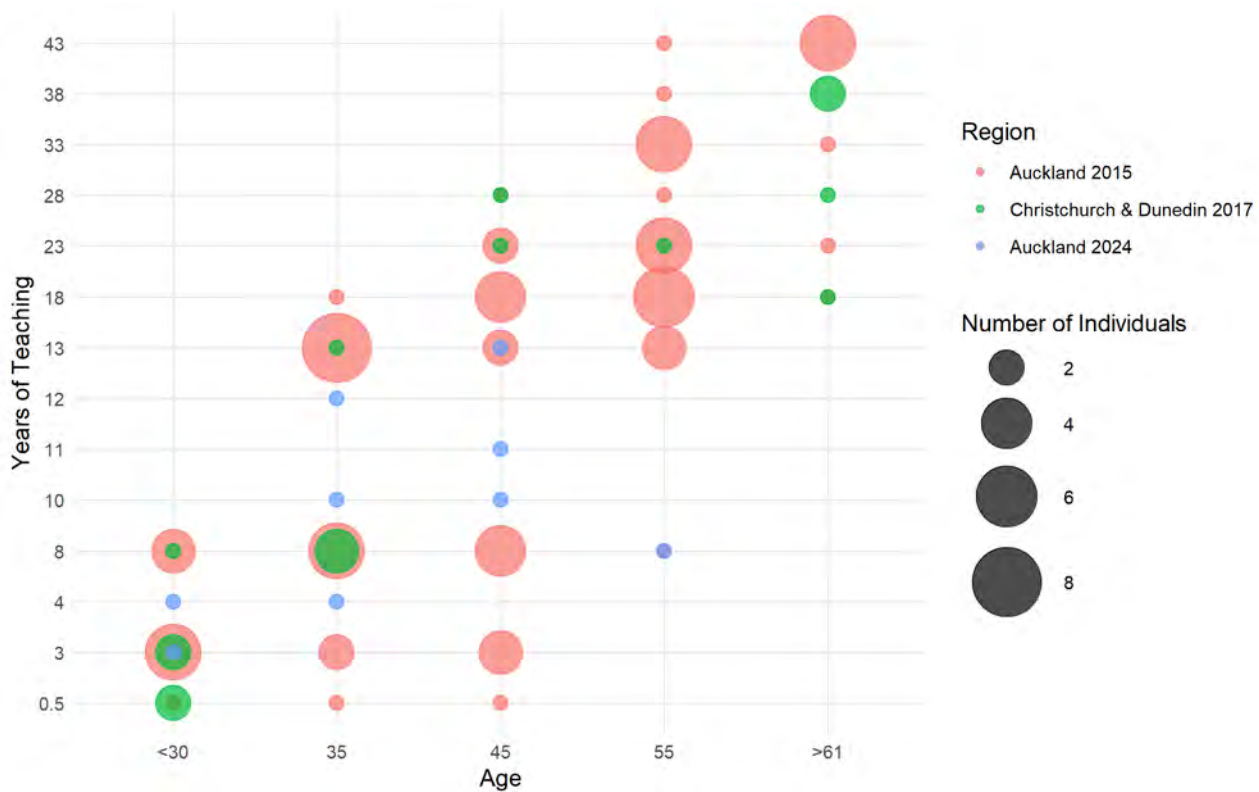


Figure 6.2 shows that 11% fell **below 30** and had accumulated an average of 3.8 years of teaching experience. Those ranging in age **from 30 to 39 years**, comprising 19% of the participants, brought an average of 9.6 years of teaching experience. The next age category, **40 to 49 years**, consisted of 23% of the respondents and had been teaching for an average of 13.5 years. The **50 to 59 age** bracket included a substantial 31% of the total participants who had an average teaching experience of 23 years. Finally, those **aged 60 and older** comprised 16% of the respondents, with an average teaching tenure of 34 years.

Research by the National Centre for Education Statistics (2022) reveals that approximately 55% of teachers begin their teaching journey in their early 20s, while the remaining individuals choose to start their careers later in life. More specifically, around 20% of teachers begin their teaching career between the ages of 26 and 30. NZ teachers can qualify for full retirement benefits after accumulating 30 years of

creditable service. Additionally, they can retire at age 65 with a minimum of five years of service credit or at age 55 if they have met the rule of 80, along with at least five years of service credit.

Interpreting the spread of 'Age' versus 'Teaching experience', the following can be concluded:

Figure 6.2 reports an average age of 44.9 ± 12.7 [SD]. The median age is 45 years. The nearly identical mean and median for age suggest a symmetric distribution without the skewing effect of outliers. This indicates that the sample might accurately represent the broader population in terms of age distribution (Statistics New Zealand, 2023).

For 'Years of Teaching experience', **Figure 6.2** reports a teaching experience average of 15.9 ± 11.8 [SD]. The SD of 11.8 years highlights a wide distribution in teaching experience. The median is 13 years of teaching experience. The difference between the mean and median for teaching experience reinforces the notion of a right-skewed distribution, since 70% have an average of 23.5 years of teaching experience.

The study results in the text show a breakdown of the percentage of participants in different age groups and their corresponding average teaching experience. The findings indicate a trend where older teachers have more years of teaching experience, which aligns with the general understanding that teaching experience accumulates over time.

The information provided is somewhat consistent with the literature from the National Centre for Education Statistics, as both sources highlight the relationship between age and teaching experience. Although the text focusses on the distribution of teaching experience among different age groups in a specific study sample, the literature of the National Centre for Education Statistics provides a broader perspective on the age at which teachers typically begin their careers.

Furthermore, the retirement eligibility criteria for NZ teachers mentioned in the text support the idea that teaching is a profession where experience plays a significant role in determining retirement benefits and age-based qualifications for retirement. This aligns with the notion that teaching experience is an important factor in the

career trajectory of educators.

Therefore, the study's results on age distribution and teaching experience, along with the information from the National Center for Education Statistics and the retirement eligibility criteria for NZ teachers, collectively contribute to the existing literature on the relationship between age, experience, and retirement benefits in the teaching profession.

6.1.3 Questionnaire design: Evaluation of classroom ventilation and user experience

Table 6.2 outlines the categories in which the questions have been classified.

TABLE 6.2: *Categorisation of Questionnaire Questions by Focus Area*

Category	Questions	Reasoning
Accessibility	Q1: Usability	Focuses on the ease of use of window and door hardware, directly relating to the accessibility of environmental controls.
Functionality	Q3: Adequacy of ventilation; Q4: Functionality under adverse conditions; Q5: Design and ventilation	Related to how effectively windows function, their robustness under conditions, and how their design affects ventilation.
Implications	Q2: Ventilation habits; Q6: Various concerns (ventilation, cleanliness, teaching and learning environment, maintenance and management); Q7: Environmental distraction; Q8: Safety	These questions cover broader implications such as habitual ventilation practices, cleanliness, environmental quality, noise distractions, and safety concerns when windows are open.

The construct of the questions revolves around the accessibility, functionality and implications of window and door use in classroom environments, specifically as they relate to ventilation and the internal classroom experience during teaching hours (09:00 and 15:00). These questions bridge the physical aspects of the classroom environment with the perceptions and behavioural intentions of the teaching staff.

This categorisation helps organise the questions according to their main themes, facilitating more accessible analysis and interpretation of the data collected from the questionnaire.

6.1.4 Questionnaire analysis

The survey employs a 5-point Likert scale for the following questions, offering respondents a range of options: 1 (Strongly Disagree), 2 (Disagree), 3 (Neither Agree nor Disagree), 4 (Agree), and 5 (Strongly Agree). This widely-used format enables a detailed evaluation of participants' opinions, effectively measuring the strength of their responses from complete disagreement to full agreement (Joshi et al., 2015). To simplify the analysis and presentation of results, the responses will be consolidated: 'Agree' and 'Strongly Agree' will be combined, as will 'Disagree' and 'Strongly Disagree', resulting in cumulative totals for each category.

Question 1 - Are the mechanisms of the windows and doors, such as handles, fasteners, and locks, user-friendly in terms of their ease of opening and closing?

The results indicate that 59% of participants agree (15% strongly agree and 44% agree) that they found the hardware elements, such as handles, fasteners and locking mechanisms, user-friendly. Conversely, 31% (2% strongly disagree and 29% disagree) of participants had an unfavourable view, while 9% maintained a neutral stance.

Figure 6.3 shows responses to the user-friendliness of window and door mechanisms categorized by age groups.

FIGURE 6.3: Question 1 - Are the mechanisms of the windows and doors, user-friendly in terms of their ease of opening and closing? (by Age Group)

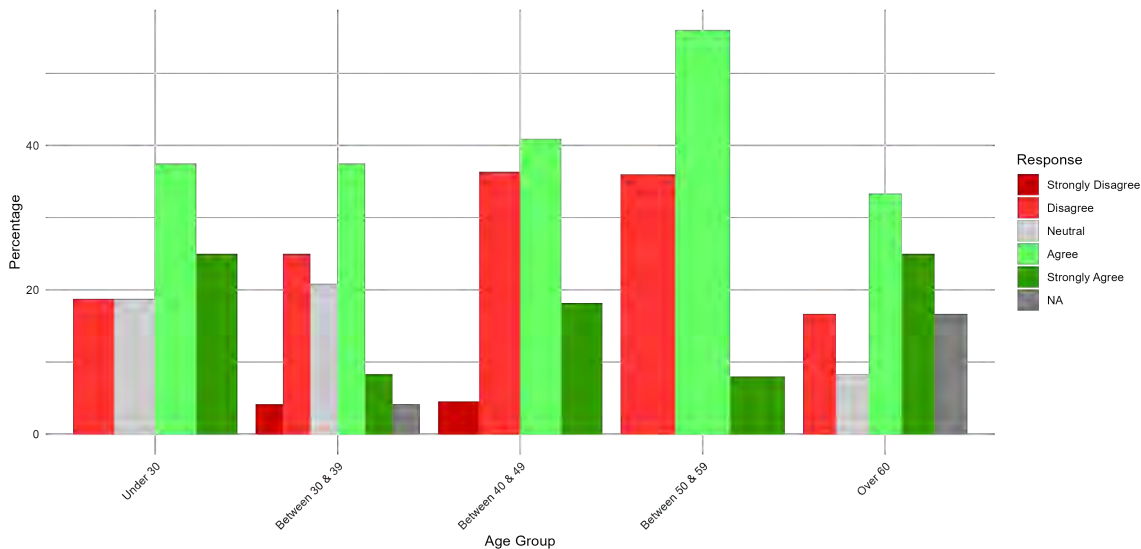


Figure 6.3 reveals varied perceptions of window and door mechanisms across age groups. **Younger teachers (under 30)** demonstrated high satisfaction, with 63% finding the mechanisms unchallenging. The age group **30-39** showed less agreement, with only 46% expressing contentment. Teachers **aged 40-49** reported increased satisfaction, as 59% agreed on the user-friendliness of the mechanisms. The age group **50-59** exhibited the highest levels of satisfaction, with 64% strongly agreeing on the ease of use, despite some dissenting opinions. Lastly, **over 60** teachers generally found the mechanisms user-friendly, with 58% in agreement.

A Wilcoxon signed rank test with continuity correction revealed a statistically significant difference in the median user-friendliness ratings for the mechanisms of the windows and doors from the neutral point on the Likert scale ($V = 2676$, $p = 0.0005$). **The data suggested a trend towards agreement that the mechanism of the windows and doors was user-friendly, with a median rating of 3.49.**

Expanding on these inferences, it is clear that understanding user satisfaction with window and door mechanisms can provide valuable information for product design, marketing, and targeted improvements. Currently, window and door mechanisms are typically classified as residential or commercial. However, considering the environment and specific user needs in educational settings, there may be a

compelling argument for establishing a separate category designed for schools.

In schools, primary users are not just teachers but also students, who frequently interact with windows and doors. An important aspect to consider is the size of the children's hands compared to the handles. Standard commercial or residential designs may not adequately account for the smaller hand sizes of children, potentially making handles difficult to grip and operate.

Question 2 - Do you open the windows each time you teach a class?

The results indicate that a total of 39% of the respondents (6% strongly agree; 33% agree) reported having a positive response, which means that they tend to open windows while teaching. On the other hand, 36% of the participants (4% strongly disagreeing; 32% disagreeing) indicated that they did not open windows. Meanwhile, 26% of the survey respondents remained neutral on this matter.

Figure 6.4 shows the responses to whether teachers open windows each time they teach a class.

FIGURE 6.4: *Question 2 - Do you open the windows each time you teach a class? (by Age Group)*

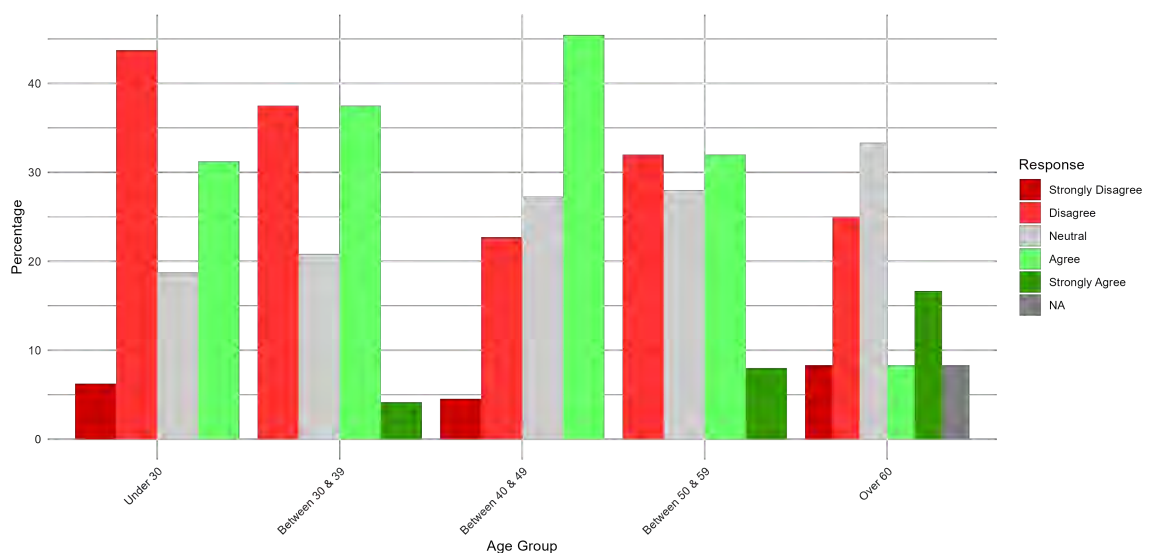


Figure 6.4 illustrates the varied behaviour of window opening between age groups during teaching. **Younger teachers (under 30)** predominantly disagree (50%) with

consistent window opening, while 31% agree. The **30-39 age group** shows mixed responses: 42% agree, 38% strongly disagree, and 21% neutral. **Teachers aged 40-49** exhibit greater agreement (45%) versus disagreement (27%). The age bracket **50-59** demonstrates 40% agreement and 32% disagreement. **Over 60 teachers** display the highest uncertainty (33% neutral) and disagreement (33%), indicating diverse practices.

A Wilcoxon signed rank test with continuity correction ($V = 1436.5$, $p = 0.605$) revealed no statistically significant difference in window opening frequency during class, aligned with the neutral point of the Likert scale. **These findings indicate no clear trend towards frequent or infrequent window opening among teachers.**

Question 3 - Does having windows and doors open contribute to a comfortable classroom environment?

The results show that 76% of the respondents responded favourably, suggesting that opening windows contributes to a comfortable classroom atmosphere. In contrast, a minority of 16% disagrees with this sentiment, expressing discomfort when windows are open in classrooms. Additionally, a small fraction of 8% of the participants took a neutral position on this issue.

Figure 6.5 details whether having windows and doors open contributes to a comfortable classroom environment.

FIGURE 6.5: Question 3 - Does having the windows and doors open contribute to a comfortable classroom environment? (by Age Group)

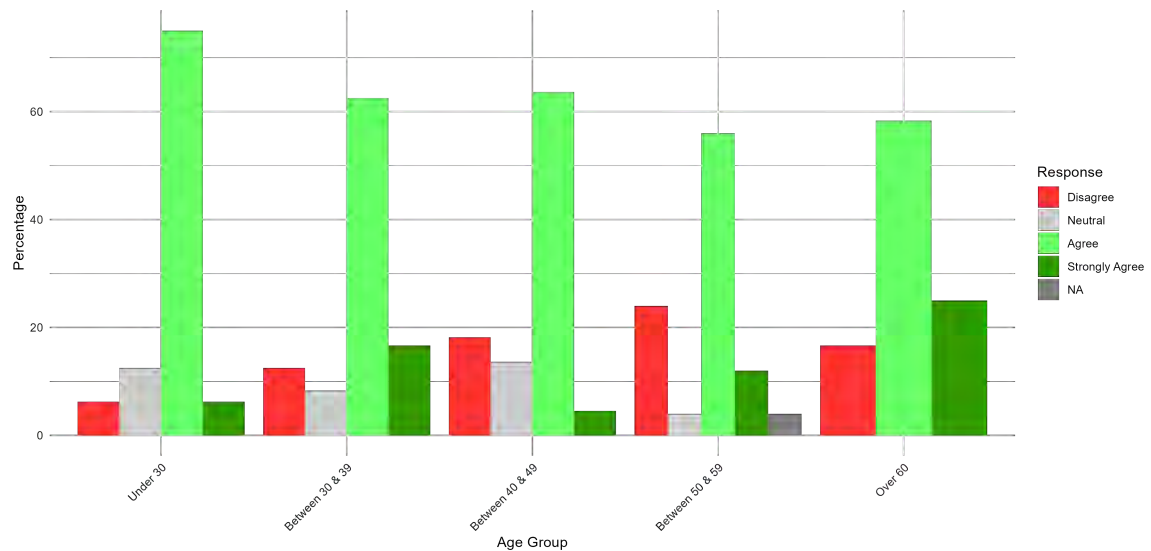


Figure 6.5 demonstrates a wide agreement between age groups that open windows and doors contribute to classroom comfort with varying intensity. **Younger teachers (under 30)** (81% agree), followed closely by those **over 60** (83% agree) show the highest consensus. The **30-39 age group** exhibits 79% agreement with minor dissent (13%). Both **40-49** and **50-59** age brackets display 68% agreement, with some neutral or dissenting responses. These findings suggest a general preference for open-air classroom environments, with slight variations between age demographics

A Wilcoxon signed-rank test with continuity correction ($V = 3463$, $p < 0.001$) revealed a significant difference in participants' perceptions of open windows and doors contributing to classroom comfort. The tight 95% confidence interval (3.99 to 4.00) **strongly indicates general agreement that fresh air from open windows and doors enhances classroom comfort.**

Question 4 - Can windows be opened on windy days?

The results show that nearly half of the respondents, with 48% responding positively (7% strongly agreeing and 41% agreeing), suggesting that windows can be opened during windy days. In comparison, 41% of the participants (3% strongly disagree; 38% disagree) stated that the windows could not be opened on such days.

Furthermore, 11% of the surveyed remained neutral on this topic.

Figure 6.6 indicates responses to whether windows can be opened on windy days.

FIGURE 6.6: Question 4 - Can windows be opened on windy days? (by Age Group)

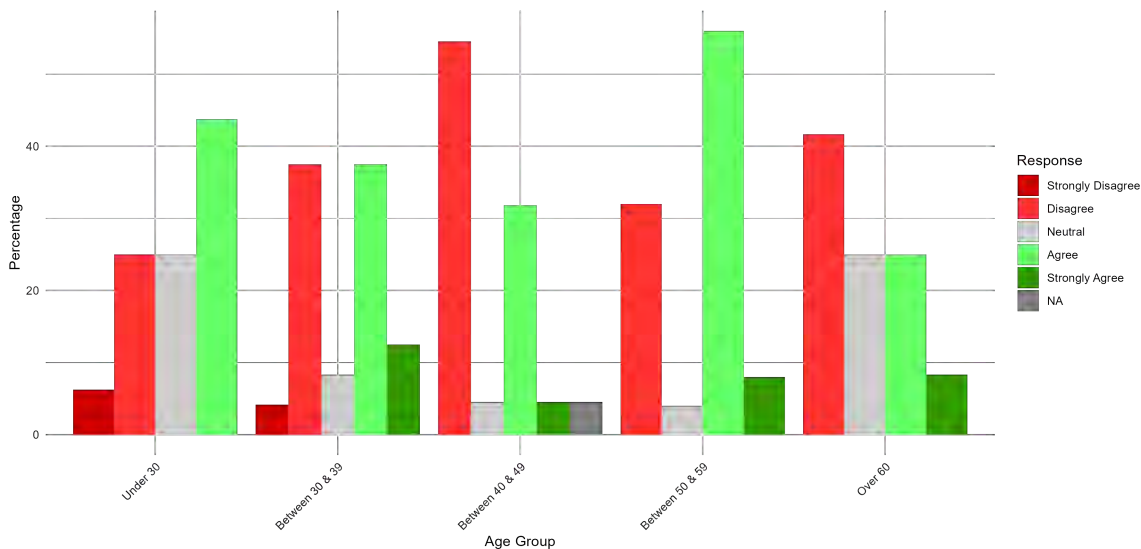


Figure 6.6 illustrates diverse perspectives on opening windows on windy days across age groups. **Younger teachers (Under 30)** show mixed opinions: 44% agree, 25% neutral, and 31% disagree. The **30-39 age group** leans towards agreement (50%), while **40-49-year-olds** predominantly disagree (55%). **Teachers aged 50-59** show the strongest agreement (64%), with minimal opposition. **Over 60 teachers** have divided opinions: 44% agree and 31% disagree.

A **Wilcoxon signed-rank test with continuity correction** ($V = 2161$, $p = 0.25$, 95% CI [2.99, 3.00]) revealed no significant differences between the median response and the test value of 3 regarding window opening on windy days. The estimated pseudo median of 3.00 **provided insufficient evidence to reject the null hypothesis**, suggesting neutral or varied opinions on this practice across the sample.

Question 5 - Do the design and type of windows and doors chosen provide adequate ventilation?

The results reflect that 64% of survey participants (5% strongly agree; 59% agree) had affirmative views, signifying that the style and kind of doors and windows installed

allowed for sufficient ventilation. In contrast, 21% of those surveyed (3% strongly disagreeing; 18% disagreeing) voiced the opinion that the ventilation provided is inadequate. Meanwhile, 14% of participants opted for a neutral viewpoint on the subject.

Figure 6.7 depicts responses regarding whether the design and type of windows and doors provide adequate ventilation.

FIGURE 6.7: Question 5 - Do the design and type of windows and doors chosen provide adequate ventilation? (by Age Group)

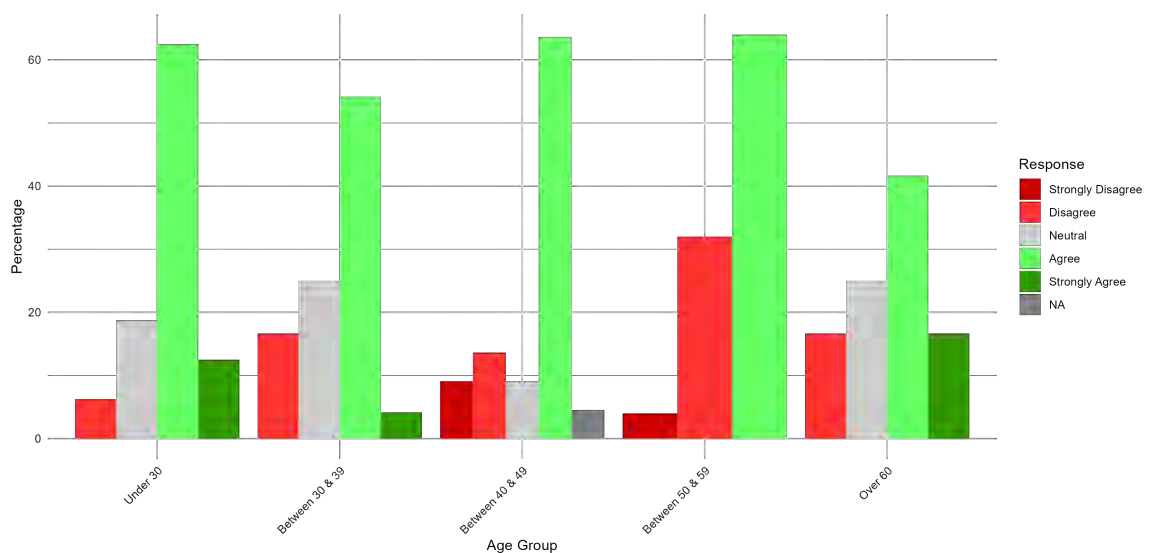


Figure 6.7 demonstrates general agreement across age groups that window and door designs provide adequate ventilation, with varying satisfaction levels. **Younger teachers (under 30)** show the highest satisfaction (75% agree), while **30-39** and **over 60** age groups both report 58% agreement, with some uncertainty and dissent. **Teachers aged 40-49 and 50-59** indicate 64% agreement, though the latter group shows higher disagreement (36%).

A Wilcoxon signed-rank test with continuity correction revealed a statistically significant difference in participant ratings of ventilation adequacy related to window and door designs ($V = 2635.5$, $p < 0.001$, 95% CI [3.00, 3.99]). **The results suggest that the selected designs are effective for ventilation, as participants rated them as better than adequate.**

Question 6 - Does your classroom have an odour, particularly after activities or after the weekend?

The results show that a majority, 58% of survey participants (16% strongly agreeing; 42% agreeing), had a positive reaction, affirming their agreement with the presence of an odour. In opposition, 30% of respondents (7% strongly disagree; 23% disagree) reported that they do not perceive any odour. Another 11% of the respondents remained impartial, neither agreeing nor disagreeing with the statement regarding the presence of odour.

Figure 6.8 details responses to whether classrooms have an odour, particularly after activities or following the weekend.

FIGURE 6.8: Question 6 - Does your classroom have an odour, particularly after activities or following the weekend? (by Age Group)

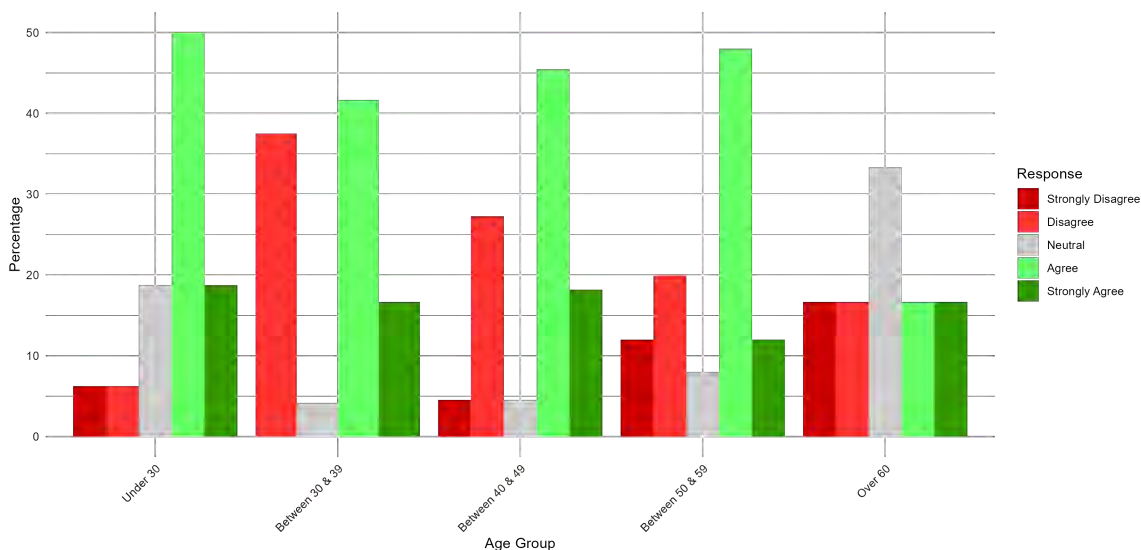


Figure 6.8 illustrates the varied perceptions of classroom odours after activities or weekends in all age groups. **Younger teachers (under 30)** predominantly agree (69%) this is an issue, with some uncertainty (19% neutral). The age group **30-39** shows mixed opinions: 58% agree, 38% disagree. **Teachers aged 40-49 and 50-59 years** show similar patterns (64% and 60% in agreement, respectively, with 32% disagreement in both groups). In contrast, **teachers older than 60** are evenly divided (33% each) between neutral, disagreed, and strongly disagreed responses, suggesting age-related differences in perception or tolerance of odours in classroom

environments.

A Wilcoxon signed rank test with continuity correction showed a statistically significant difference in the reported odour levels compared to the neutral score of 3 on the Likert scale ($V = 2618, p = 0.0037$). **The findings suggest that the intensity of the odour in the classroom fluctuates, especially after activities or weekends.**

Question 7 - Does outside noise discourage you from opening windows during class?

The results illustrate that just over half of the respondents 53% (15% strongly agree; 38% agree), responded positively, indicating that outside noise deters them from opening their windows. On the other hand, 32% of the participants (6% strongly disagreeing; 26% disagreeing) expressed that they are not hindered by opening windows despite the noise outside. Meanwhile, 14% of those surveyed had a neutral view of the impact of noise on their window opening habits.

Figure 6.9 depicting responses to whether outside noise discourages teachers from opening windows during class.

FIGURE 6.9: Question 7 - Does outside noise discourage you from opening the windows during class? (by Age Group)

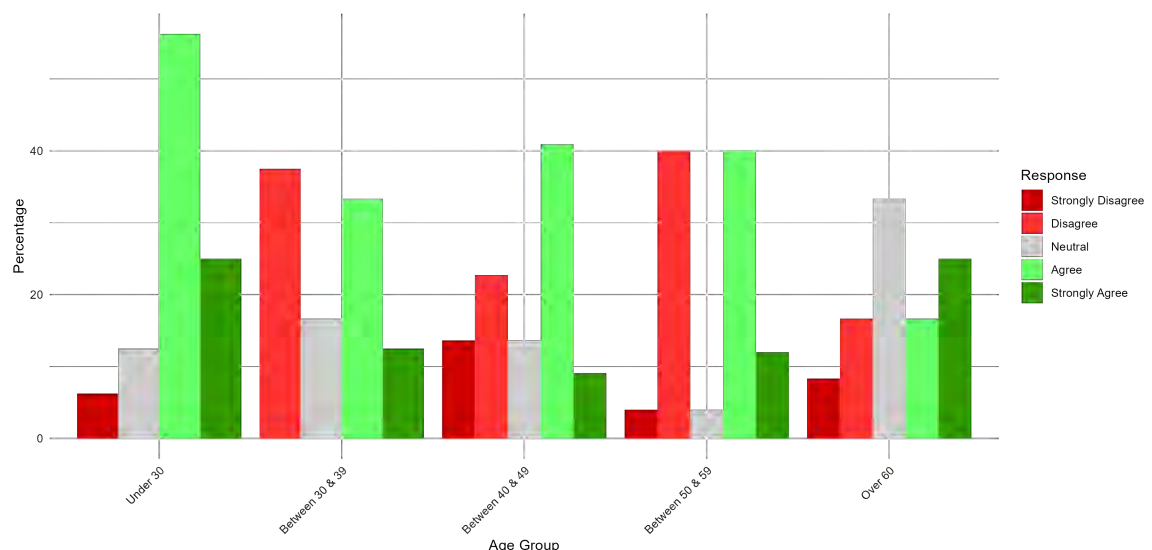


Figure 6.9 demonstrates varied perceptions between age groups regarding outside noise as a deterrent to opening windows during class. **Younger teachers (under 30)** show the highest agreement (81%), while other age groups display more diverse

opinions. The **30-39** and **40-49** age brackets exhibit similar patterns (46% and 50% agreement, respectively), with notable disagreement (38% and 36%) and neutrality. **Teachers aged 50-59** lean towards agreement (52%), with substantial disagreement (44%). **Over 60 teachers** show the most varied responses: 42% agree, 33% neutral, and 25% disagree, suggesting age-related differences in noise sensitivity or classroom management strategies.

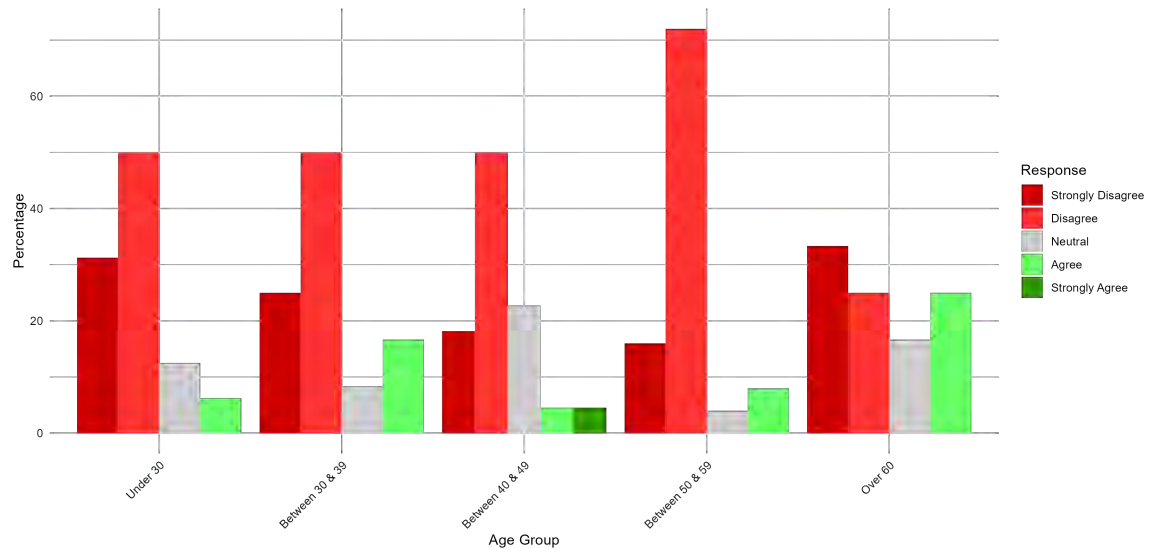
A Wilcoxon signed rank test with continuity correction did not show a significant impact of external noise on the decision to open classroom windows ($V = 2360$, $p = 0.013$). The responses indicated a neutral position, **suggesting that outside noise does not discourage teachers from opening windows during class time.**

Question 8 - Opening the windows creates a safety hazard for students, within the classroom or outside?

Results show that a small portion (12%) of the respondents (11% agree; 1% strongly agree) had a positive response, indicating they believe that opening classroom windows poses a safety risk. In contrast, a significant majority of 76% (23% strongly disagree; 53% disagree) argue that opening windows is not a safety hazard. In addition 12% of the participants chose to remain neutral on this issue.

Figure 6.10 compares the ages of teachers and their responses to the statement 'Opening the windows creates a safety hazard for students, whether within the classroom or outside.'

FIGURE 6.10: Question 8 - Opening the windows creates a safety hazard for the students, whether within the classroom or outside? (by Age Group)



Under-40 teachers (Figure 6.10) exhibit increased safety concerns (81% under 30, 75% 30-40) regarding open windows, with strong agreement predominating. Significant disagreement exists, yet the agreement ratio surpasses other age groups. **40-50 teachers** show 68% disagreement, suggesting increased risk aversion or hazard awareness. **Over-50 teachers** strongly disagree (73%), indicating age-related shift in safety perceptions.

A Wilcoxon signed rank test with continuity correction revealed a significant perception that opening classroom windows poses a safety hazard to students ($V = 427.5, p < 0.001$). The data suggested a **consensus among the respondents that this action presents potential safety risks.**

A correlation analysis using Spearman rank-order correlation was conducted to explore the relationships between variables further.

Correlation analysis using Spearman's rank-order correlation

This section will examine Spearman's rank-order correlation analysis results (Figure 6.11).

FIGURE 6.11: *Spearman's Rank-Order Correlation Matrix Showing p-values and ρ (rho) Values*

	Question 1	Question 2	Question 3	Question 4	Question 5
Question 1 <i>Usability</i>					
Question 2 <i>Ventilation habits</i>	p-value = 0.536 rho = -0.063				
Question 3 <i>Adequacy of ventilation</i>	p-value = 0.002 rho = 0.310	p-value = 0.406 rho = 0.085			
Question 4 <i>Functionality</i>		p-value = 0.153 rho = 0.146			
Question 5 <i>Design and ventilation</i>			p-value = <0.001 rho = 0.531		
Question 6 <i>Odour concerns</i>	p-value = 0.001 rho = -0.321		p-value = <0.001 rho = -0.357		p-value = 0.012 rho = -0.250
Question 7 <i>Noise</i>		p-value = 0.753 rho = -0.032			p-value = 0.139 rho = -0.150
Question 8 <i>Safety</i>		p-value = 0.912 rho = -0.011			p-value = 0.258 rho = -0.115

Significant correlation

This statistical method assesses the strength and direction of the association between the ranked variables. However, it is important to note that, as previously discussed, not all questions within the data set are related. Consequently, this results in an incomplete correlation matrix, reflecting the selective relationships among the variables.

Table 6.3 summarises the interpretation and perceptions resulting from (Figure 6.11).

TABLE 6.3: Interpretation and Perceptions resulting from Spearman's Rank-Order Correlation Matrix

Questions	p -value	ρ (ρ)	Interpretation and Perception
Q1 and Q2	0.536	-0.06	No significant correlation; very weak negative relationship. No link between easy-to-use mechanisms and frequent window opening.
Q1 and Q3	0.002	0.31	Significant moderate positive correlation. Easier window and door operation may enhance perceived air comfort.
Q1 and Q6	0.001	-0.32	Significant moderate negative correlation. Easier window mechanisms may reduce odours through better ventilation.
Q2 and Q3	0.406	0.08	No significant correlation; very weak positive relationship. Frequent window opening does not necessarily improve perceived air comfort.
Q2 and Q4	0.153	0.14	No significant correlation; weak positive relationship. Window opening frequency unrelated to beliefs about windy day use.
Q2 and Q7	0.753	-0.03	No significant correlation; negligible negative relationship. Window opening during teaching unrelated to noise concerns.
Q2 and Q8	0.912	-0.01	No significant correlation; negligible negative relationship. No notable link between window opening during teaching and safety concerns.
Q3 and Q5	<0.001	0.53	Significant moderate to strong positive correlation. Perceived ventilation adequacy correlates with belief in fresh air's comfort benefits.
Q3 and Q6	<0.001	-0.35	Significant moderate negative correlation. Improved ventilation may decrease classroom odours.
Q5 and Q6	0.012	-0.25	Significant weak to moderate negative correlation. Better window and door ventilation may reduce classroom odours.
Q5 and Q7	0.139	-0.15	No significant correlation; weak negative relationship. Minimal negative correlation between perceived ventilation adequacy and noise-related reluctance to open windows.
Q5 and Q8	0.258	-0.12	No significant correlation; very weak negative relationship. Perceived ventilation adequacy inversely correlates with window safety concerns.

Overall, the results (Table 6.3) suggest that user-friendly window/door mechanisms and adequate ventilation design are associated with improved classroom comfort, reduced odours and positive perception of fresh air. However, noise and safety concerns do not significantly impact window-opening behaviour or ventilation perceptions.

6.1.5 Inverter heat-pump inquiry

Question 9 - Do you prefer to use the Inverter heat pump rather than opening the windows?

Of the initial 99 responses, 26 are not applicable, leaving a revised sample size of 73.

The results reveal a divided opinion on the preference for the heat pump over window opening. 40% disagree, while 41% favour (31% agree, 11% strongly agree). 19% remain neutral, possibly due to indecision, lack of information, or insignificance of the issue. Substantial support on both sides indicates clear division and the

absence of overwhelming consensus among participants.

Question 9a - If there is an Inverter heat pump: Do you use it in Summer or Winter?

Figure 6.12 illustrates the use of the inverter heat pump in Summer and Winter.

FIGURE 6.12: Question 9a: Inverter Heat Pump Usage in Summer and Winter

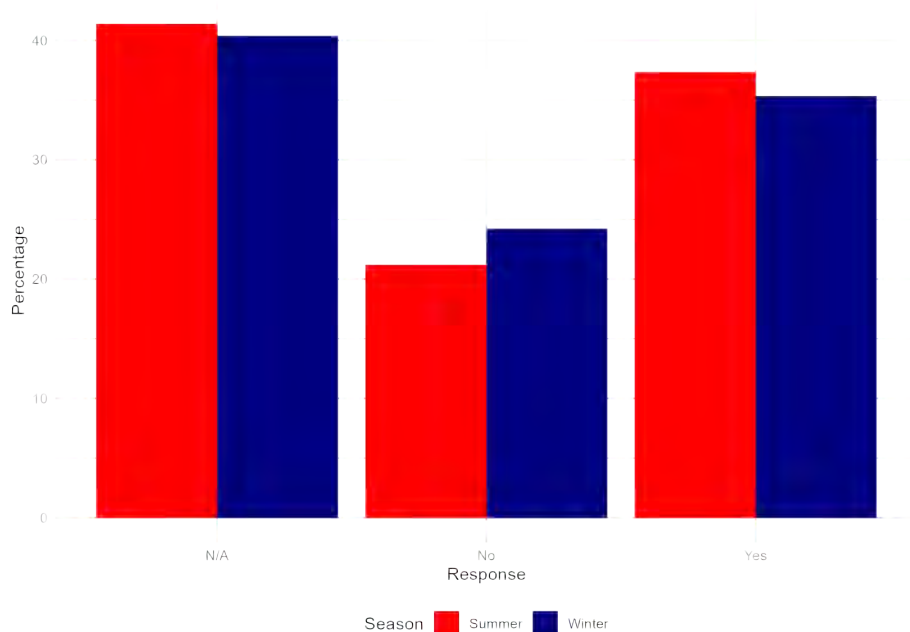
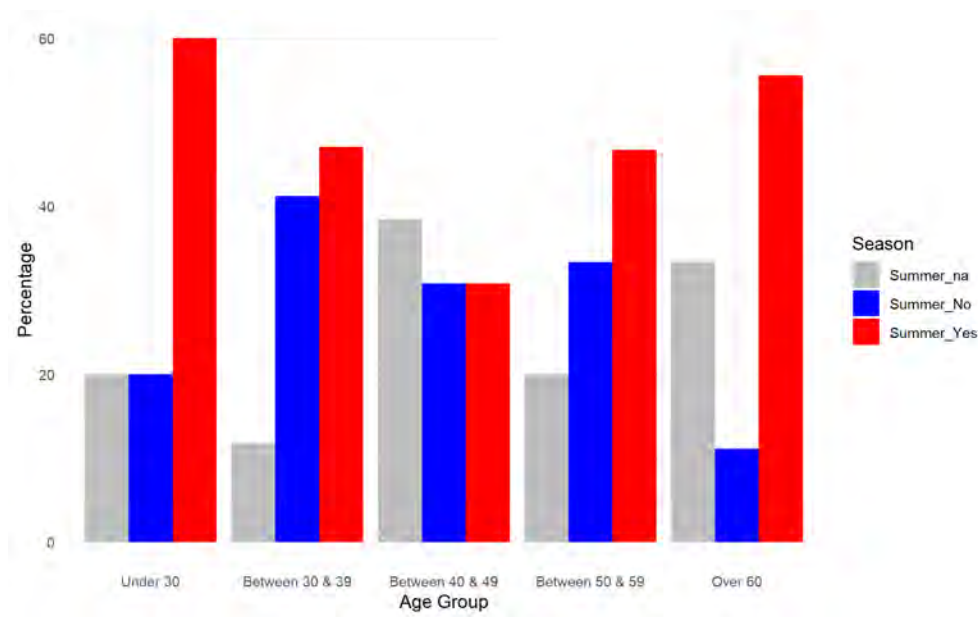


Figure 6.12 data reveal seasonal variations in the usage of the inverter heat pump. In winter, 35% reported usage, 24% non-usage, and 40% abstained from responding despite participating in Question 9. Summer patterns show 37% usage, 21% non-usage, and 41% providing no definitive answer. The high "na" response rates in both seasons suggest possible question misunderstanding or deliberate non-response.

Question 9b - Please let me know how old you are if you answered Question 9.

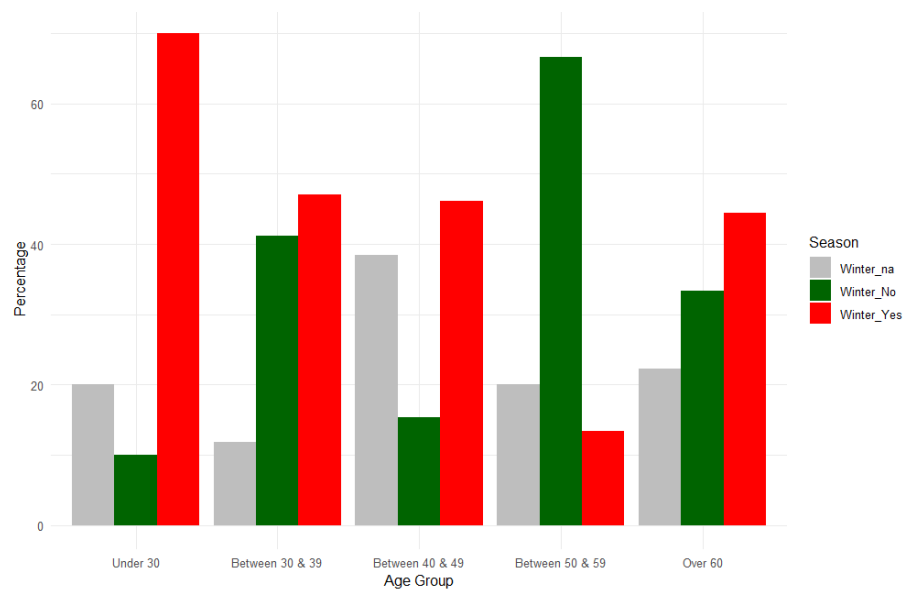
Analysing the bar plots (Figures 6.13 and 6.14), we can observe the use of inverter heat pumps in summer in different age groups for teachers and compare them with the use in winter.

FIGURE 6.13: Question 9a: Inverter Heat Pump Used in Summer - by Age



From **Figure 6.13**, illustrates varying preferences for the use of inverter heat pumps among different age groups of teachers during the summer. The younger and older age groups show higher usage, while the middle age groups show more variability.

FIGURE 6.14: Question 9a: Inverter Heat Pump Used in Winter - by Age



The comparative age analysis of winter vs. summer usage (From **Figures 6.13** and **6.14**) reveals distinct patterns between age groups. Under-30s show very high usage in both seasons, with winter (70%) surpassing summer (60%) and minimal

non-responses. The 30-39 group maintains stable usage patterns between seasons. Ages 40-49 exhibit a noticeable increase in winter usage (46%) compared to summer (31%), with higher summer non-usage (31% vs. 15% in winter). A significant shift occurs in the 50-59 group, with winter non-usage rising dramatically (67% vs. 33% in summer) and lower winter usage (13% vs. 47% in summer). The over-60s demonstrate a slight decrease in usage in winter (44%) compared to summer (56%). These variations suggest age-related preferences and potentially different comfort needs between seasons.

Different age groups show different seasonal preferences. For example, the 50 and 59 age group shows significantly higher usage in summer (47%) compared to winter (13%). This suggests potential seasonal influences on the decision to use inverter heat pumps, possibly due to varying comfort levels or perceptions of necessity during different times of the year.

Understanding different age profiles

1. **Under 30 age group:** Higher Yes responses in both seasons suggest a strong preference or need for inverter heat pumps year-round.
2. **30 and 39 age groups:** Stable usage across seasons indicates a consistent view or reliance on inverter heat pumps.
3. **40 and 49 age groups:** Fluctuations in usage suggest varying needs or preferences based on season.
4. **50 and 59 age groups:** The steady decrease in winter usage points to specific winter-related factors that discourage heat pump use.
5. **Over 60 age group:** Lower usage discrepancy between seasons, but still notable.

In conclusion, teachers have significant differences in the use of inverter heat pumps in different age groups between winter and summer. The younger and older age groups show high usage in both seasons.

This interpretation assumes that the respondents' choices are based on preference or need rather than external constraints, such as inverter heat pump availability or school policies. To derive more definitive conclusions, additional context is required

on the specific circumstances, regional climate conditions, and the condition of the inverter heat pump systems in question.

Analysis of environmental and functional impacts of inverter heat pump usage

In analysing the relationship between Q9 - "I use the inverter heat pump" and other variables (**Table 6.4**), it is important to consider the potential role of Q1, Q4, Q6, Q7 and Q8 as confounders.

TABLE 6.4: Correlation Analysis of Q9 with Select Questions (Q1, Q4, Q6, Q7, Q8)

Question 1 <i>Usability</i>	Question 9		Interpretation and Perception
	p -value = 0.674 ρ = -0.083		
			No significant correlation. Statistical analysis reveals no significant correlation between inverter heat pump usage and window/door operational ease of use, indicating independent factors in classroom environment management.
Question 4 <i>Functionality</i>	p -value = 0.978 ρ = -0.005		No significant correlation. Inverter heat pump usage and window functionality during windy conditions demonstrate no statistically significant relationship, suggesting independent considerations in classroom ventilation strategies.
Question 6 <i>Odour concerns</i>	p -value = 0.038 ρ = 0.380		Significant moderate positive correlation. Inverter heat pump usage correlates with classroom odour prevalence, indicating increased odorous conditions especially post-activities or weekends.
Question 7 <i>Noise</i>	p -value = 0.096 ρ = 0.310		Moderate positive correlation. A moderate correlation exists between Inverter heat pump usage and reluctance to open windows due to external noise. However, statistical significance at the 0.05 level is not achieved, warranting cautious interpretation of this relationship.
Question 8 <i>Safety</i>	p -value = 0.980 ρ = 0.005		No significant correlation. Statistical analysis indicates no significant correlation between inverter heat pump usage and perceived window-opening safety hazards.

Significant correlation

Statistical analysis of classroom inverter heat pump usage reveals various relationships with environmental factors. There are no significant correlations between heat pump use and window / door usability, functionality in windy conditions, or perceived safety hazards. However, a significant moderate positive correlation ($p=0.038$, $\rho=0.380$) emerges between heat pump use and classroom odour prevalence, particularly after activities or weekends. A moderate positive correlation ($\rho = 0.310$) is observed between heat pump use and reluctance to open windows due to external noise, although it is not statistically significant at the 0.05

level ($p=0.096$). These findings suggest that, while the use of heat pumps does not affect most aspects of the management of the classroom environment, it can influence decisions related to air quality and noise. ventilation.

Question 9c - In which region of New Zealand do you teach?

Schools are distributed between the North and South Islands at a ratio of 75% to 25%, respectively, according to the data from Figure.nz (Year). However, within a sampled set of 99 schools, 83 were located in Auckland (North Island), while only 16 were based in Christchurch and Dunedin (South Island), resulting in a distribution skew of 83% to 17%.

The disproportionate sample could affect the results in several ways:

1. **Representation bias:** The findings may not accurately represent the educational environment of the South Island if the characteristics of the schools differ significantly from those of the North.
2. **Generalisability:** It becomes challenging to generalise the results to all schools in NZ as the sample does not reflect the actual 75% to 25% split.
3. **Statistical bias:** The over-representation of Auckland schools could skew statistics such as average school size, resource allocation, or student performance, given the unique socioeconomic factors of the region.
4. **Regional insights:** Regional insights might be missed or under-represented, such as the impact of different regional policies or practices on education.
5. **Cultural diversity:** The cultural diversity within schools might be misrepresented, as the North and South Islands might have different demographic profiles that influence cultural practices.

The PI wishes to highlight the imbalanced sample, as the data have already been collected and exhibit an imbalance that does not reflect the true proportional split between the North and South Island schools. Importantly, any report or publication should thoroughly discuss the limitations of the sample imbalance. This transparency will allow the reader to interpret the results better and understand the context of the study findings.

6.1.6 Survey response discussion

The findings of our study explore the user-friendliness of window and door mechanisms in educational settings and their impact on classroom comfort and ventilation. Based on survey responses and analysis, several critical insights and observations parallel the existing literature, contributing to a deeper understanding of the topic.

The research findings and the literature support each other in several key areas regarding the implications of age and teaching experience implications for TC&V behaviours:

1. Age implications:

- **Perception differences:** The research found that 70% of the respondents were older than 40 years, suggesting a potentially more sensitive group to TC&V issues. This aligns with Griefahn et al. (2001) and Romero et al. (2023), who confirm that older individuals might be more sensitive to temperature fluctuations and air quality, potentially affecting their window opening behaviours.
- **Adaptability:** The study showed that 11% of the respondents were under 30, representing a younger group that could be more adaptable to technological solutions. This is supported by Stern (2000), who suggests that younger individuals may be more able to adapt to technological solutions for monitoring and adjusting TC&V. In comparison, older people might prefer manual controls such as opening windows.
- **Health concerns:** With 16% of teachers over 60 years and 31% between 50-59 years, the research indicates a significant proportion of older teachers who may have increased health concerns. Vu et al. (2019) corroborate this, noting that older people can exhibit more proactive behaviour with window openings to ensure adequate ventilation due to health concerns.
- **Comfort level:** The substantial proportion of older teachers (47% above 50) in the study suggests potential variations in comfort levels. This is supported by Griefahn et al. (2001), who confirm that age-related physiological changes can affect comfort levels, and older adults can potentially find draughts more uncomfortable.

2. Teaching experience implications:

- **Habitual behaviour:** The research found that teachers aged 50 to 59 years had an average of 23 years of teaching experience, suggesting established routines. This aligns with Kramer et al. (2023) and Schweiker et al. (2020), who support that experienced individuals may have established routines for managing TC&V.
- **Knowledge and awareness:** The study showed that 70% of the respondents had an average of 23.5 years of teaching experience, indicating a highly experienced sample. Hancock (2020) and Schweiker et al. (2020) support that more experienced teachers may better understand TC&V importance, influencing their window-use behaviours.
- **Educational impact:** The research revealed a wide range of teaching experience, from an average of 3.8 years for those under 30 to 34 years for those 60 years and older. Zapata et al. (2023) confirm that experienced teachers can approach classroom management, including TC&V, differently from newer teachers, supporting the potential for various approaches to window use based on experience level.

For Questions 1 through 9, the research findings are consistent with and supported by the literature, as summarised here.

1. Our data shows that younger teachers, particularly those under 30, find the operation of window and door mechanisms more challenging, which aligns with observations by Zhang (2016) suggesting that accessibility and ease of use are critical factors for effective classroom ventilation.
2. Middle-aged teachers (40-59) consistently utilise windows for ventilation, indicating a strong preference for natural air circulation. This tendency supports findings by Diaz (2021) that highlight the importance of user behaviour in managing CO₂ levels through window operations.
3. The survey responses indicate a strong belief in the comfort benefits of open windows across all age groups. Still, classroom odours are more pronounced among certain age demographics. Ma (2020) emphasizes the dual impact of window opening on CO₂ reduction and ambient temperature, which resonates with the findings about age-specific challenges and comfort perceptions.

4. There is a consensus on the necessity for design adaptations to make window and door mechanisms more accessible for younger teachers. This need reflects Zapata-Lancaster's (2023) calls for innovative solutions to balance ventilation and TC without excessive energy use.
5. The study mirrors the concerns highlighted by Zapata-Lancaster (2023) regarding the TC compromises during colder seasons when windows are opened for ventilation.
6. The varied safety concerns across different age groups suggest a need for age-appropriate safety training and communication strategies, reinforcing the observations by Zhang (2016) about the significance of user education in managing IEQ.
7. The study's insights into the relationship between window operation behaviours and factors like smell and noise underline the complex dynamics of maintaining IEQ, echoing Diaz's (2021) findings on the importance of balancing ventilation with other environmental comfort aspects.
8. Developing lighter, ergonomically designed mechanisms could significantly improve usability, particularly for younger teachers who struggle with current designs. This approach aligns with the literature's emphasis on addressing specific user needs to enhance overall experience and efficiency (Wall, 2016).
9. The study highlights the potential energy implications of frequent window opening during colder seasons, as discussed by Zapata-Lancaster (2023). Designing windows that allow efficient ventilation while maintaining TC should be a priority.
10. Initiating targeted training programs to educate teachers on the optimal use of windows and doors for ventilation can help mitigate issues related to CO₂ levels and odours, supporting Zhang's (2016) recommendations for improved IEQ management through informed user practices.
11. Studies such as those by Zapata-Lancaster (2023) and Ma (2020) illustrate the delicate balance between achieving good air quality through window opening and maintaining TC, often compromised in colder weather.

12. This study aligns with NIWA's (2022) and McIntosh's (2011) findings, showing that window opening practices significantly impact indoor CO₂ levels and TC but often lead to lower indoor temperatures.
13. Strategic window management could significantly improve air change rates and reduce CO₂ levels, although practical implementation remains inconsistent (Alonso et al., 2021; 2007; 2014; Gohara et al., 2022; Kulo et al., 2021; Zemitis et al., 2021). The study reveals widespread agreement (76%) on the positive impact of open doors and windows on classroom comfort (Question 3). However, only 36% of participants consistently supported opening windows each time they taught.

This integrated analysis demonstrates a strong alignment between the research findings and the supporting literature, strengthening the validity of the implications drawn from the study.

In summary, the research integrates with the broader literature by highlighting key areas where window and door mechanism designs can evolve to meet the distinct needs of education environments. Addressing user-friendly operation, supporting natural ventilation, and providing tailored training are fundamental strategies that align with contemporary findings and can lead to enhanced classroom environments.

Based on the findings and insights of this study, several recommendations for improvements and future research areas are highlighted in Chapter 8.

6.1.7 Relevance of the study

1. **Regional specificity and comprehensive assessment:** This study addresses the gap in NZ-specific IEQ research, examining unique climatic conditions, educational infrastructure, and ventilation standards. It provides a detailed assessment of thermal insulation and airtightness in primary schools in NZ, elements often overlooked in previous studies.
2. **Window-opening behaviour and advanced monitoring:** The study offers granular information on classroom window opening behaviours and their impact on CO₂ levels and TC using modern sensor technologies. This includes quantifying the effects of partial vs. full opening practices and bridging a gap in understanding practical ventilation implications.

3. **COVID-19 response and interdisciplinary approach:** The study's focus on ventilation improvements addresses ongoing pandemic concerns, evaluating strategies for maintaining safe and comfortable classrooms. The interdisciplinary approach integrates environmental science, education, cognitive psychology, and public health perspectives.
4. **Technology integration and energy efficiency:** The study examines the usage of inverter heat pumps versus natural ventilation, contributing to the dialogue on energy-efficient IEQ solutions. Insights on seasonal preferences for heat pump use complement natural ventilation strategies.
5. **Policy implications and confounding factors:** The findings directly affect NZ's educational policy and facility management. By exploring potential confounders such as window operability, outside noise, and safety hazards, the study offers a holistic approach to IEQ management, informing contextually relevant solutions.

6.1.8 Methodological reflection

Assessing this study's methodological strengths and limitations of this study is essential to evaluate the robustness of its findings and guide future research and practice. Key reflections include

1. Strengths

- **Comprehensive question coverage:** The survey's design addressed diverse aspects of user-friendliness, safety, and effectiveness of window and door mechanisms, enabling a holistic analysis from multiple perspectives.
- **Age group analysis:** Categorising responses by age groups revealed nuanced insights, offering tailored recommendations relevant to different demographics.
- **Use of Wilcoxon Signed-Rank Test:** This non-parametric test compared median differences effectively, ensuring robust analysis despite potential non-normal data distributions.
- **Spearman's Rank-Order Correlation:** This method identified relationships between ranked variables, uncovering underlying patterns that added depth to the analysis.

- **Real-world applicability:** Grounding the study in practical challenges facing teachers ensured actionable findings relevant to improving classroom environments.

2. Limitations

- **Limited scope:** The survey's sample size or geographical focus might limit the generalizability of findings as indicated by (H. Du et al., 2023).
- **Lack of diverse perspectives:** Focussing primarily on teachers can overlook crucial insights from students, administrative staff, and maintenance personnel.
- **Reliance on self-reported data:** Self-reported data can be subject to bias, which affects the validity and reliability of the results.
- **Limitations of Likert scale:** Likert scales can oversimplify responses, potentially missing nuanced differences in experiences and perceptions.
- **Snapshot in time:** Survey responses reflect conditions at a specific moment, potentially missing temporal variations such as seasonality or changing demands.
- **Contextual variability:** Various factors such as building design, local climate, and socioeconomic conditions may not be fully accounted for, affecting the relevance of the findings to different settings.

3. Future methodological improvements

- **Expand sampling:** Including a larger and more diverse sample across different regions and climates to enhance the generalizability of the findings.
- **Incorporate multiple stakeholder perspectives:** Gathering input from students, parents, administrative staff, and maintenance personnel to provide a more holistic view of the impact of window and door mechanisms.
- **Qualitative insights:** Complementing surveys with qualitative methods, such as interviews or focus groups, to capture detailed and nuanced user experiences.
- **Energy consumption analysis:** Assess the impact of window use on energy efficiency to derive solutions that balance ventilation needs with sustainability goals.

Reflecting on these methodological aspects clarifies the study's contributions and identifies areas for refinement, ensuring more robust, inclusive, and actionable insights for improving window and door mechanisms in educational settings. By addressing these limitations, future research can foster better informed decisions and more effective results for diverse educational environments.

6.1.9 Examining questionnaire reliability with Cronbach's Alpha

Cronbach's alpha, **Table 6.5** was used to measure the internal consistency reliability of the questionnaire.

TABLE 6.5: *Reliability Analysis Using Cronbach's Alpha*

Functionality questions (Q3, Q4, and Q5)						95% confidence boundaries			
raw_alpha	std.alpha	S/N	mean	sd	median_r		lower	alpha	upper
0.59	0.6	1.5	3.4	0.72	0.28	Feldt	0.42	0.59	0.71
						Duhachek	0.44	0.59	0.73

Implications questions (Q2, Q6, Q7, and Q8)						95% confidence boundaries			
raw_alpha	std.alpha	S/N	mean	sd	median_r		lower	alpha	upper
0.25	0.23	0.29	3	0.6	0.01	Feldt	-0.03	0.25	0.46
						Duhachek	0.01	0.25	0.48

The analysis of the *functionality* questions yielded a Cronbach Alpha value of 0.59 (**Table 6.5**). This value falls just short of the standard benchmark of 0.7, which is generally considered the minimum for adequate internal consistency. Consequently, it suggests that these items exhibit a modest consistency among themselves. The signal-to-noise ratio of 1.5 points is on a relatively reliable scale where the variance attributed to the actual scores is predominant over the error variance (Barbera et al., 2020; Cho and Kim, 2015).

The *functionality* group of questions in **Table 6.2** exhibits moderate internal consistency, as indicated by Cronbach's alpha coefficient. Although slightly below the ideal standard, the items on the scale appear to measure a cohesive construct. To improve reliability, the scale can benefit from revisiting the item content to ensure that each question is straightforward & directly relevant. Increasing the number of questions aimed at the same construct or adjusting the existing items to more accurately reflect it could also contribute to a stronger alpha value.

Considering that the 95% confidence interval (**Table 6.5**) is 0.71 & remains above 0.45 for both Feldt & Duhachek, the scale is deemed to have an acceptable level of reliability. However, if the study requirements require higher precision, it is recommended that revisions be made to enhance this reliability score.

The scale of the *implications* group of questions in **Table 6.2** yielded a Cronbach Alpha value of 0.25 (**Table 6.5**). This level of internal consistency is below the generally accepted threshold of 0.70 needed for satisfactory reliability. Although a lower alpha can occur with fewer items on a scale, the present value denotes that the internal coherence between these items is less than ideal & does not reliably measure the same underlying construct.

It is not entirely surprising that Cronbach's alpha yielded low scores, considering the nature of the questions. Although they all pertain to the overarching theme of ventilation habits, environmental distraction, & safety, each question examines different nuanced aspects of this broad subject.

Cronbach's alpha results

A few reasons may lead to low Cronbach alpha scores:

1. **Different facets of ventilation:** Each question examines a facet of ventilation, odour, noise, safety, ease of window operation, etc. These factors, while related, could influence teacher behaviours & perceptions quite differently, contributing to less homogeneity in responses (Cho and Kim, 2015; Snow et al., 2022).
2. **Varied individual sensitivities:** The responses could vary widely because of individual sensitivities & tolerances to odour, noise, & perceptions of safety, which may not be uniformly distributed across the group of participants (Cho and Kim, 2015; Snow et al., 2022).
3. **Contextual influences:** Certain questions may be more relevant in specific contexts; for example, windy conditions may not be a significant factor in certain cases, affecting the perceived relevance of the questions related to them (Cho and Kim, 2015; Snow et al., 2022).
4. **Physical vs behavioural elements:** The questions touch on both physical (e.g. the mechanics of opening windows) & behavioural (e.g. frequency of opening

windows) aspects of ventilation, which could not strongly correlate with each other (Cho and Kim, 2015).

5. **Subjective interpretations:** The subjective interpretation of 'safety' or 'adequacy of fresh air' can vary widely based on personal experiences & beliefs, which may lead to inconsistencies in how the questions are understood & answered (Cho and Kim, 2015).

To conclude, the examination of study reliability using Cronbach's Alpha reveals moderate internal consistency for the functionality questions and low consistency for the implication questions. The diverse nature of the questions and the varied individual sensitivities contribute to this variability. Future refinements, such as revisiting the content of the item and increasing the number of questions that target the same constructs, could improve the internal consistency and reliability of the survey. Furthermore, considering the factors influencing teacher behaviour and perceptions will provide more accurate and actionable insights to improve classroom environments.

6.2 Observation study results

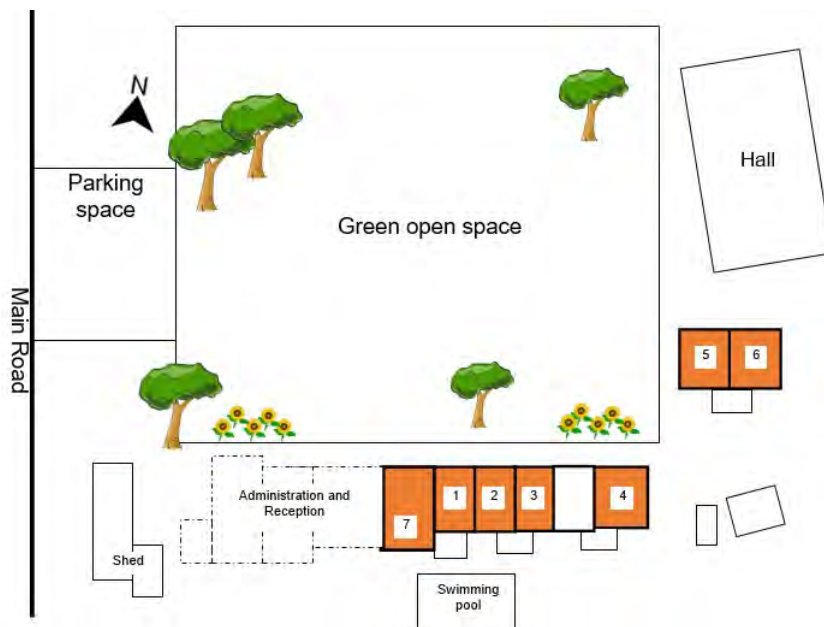
The chosen primary school, located in the temperate and generally mild climate of North Shore, Auckland, experiences an average annual temperature of 15.6 °C and receives around 1,231 mm of rainfall, according to NIWA's (2023b) report. As depicted in **Figure 6.15**, the school serves 160 students between the ages of 5 and 11 in multiage group classes, which are located approximately 90 m from the main road, which helps reduce auditory disturbances. The classrooms designated for this study are marked S1-1 to S1-3 to maintain confidentiality. The facility includes six classrooms of equal floor area and a single library space. All classrooms are on the first floor and feature doors on the north side that open directly to the playground. A system for cross ventilation is possible thanks to windows on both the classrooms' North (front) and South (back) sides. Two classrooms (S1-2 and S1-3) were removed from the study for remediation due to mould mid-term.

Observations for this study were made on March 20, 23, and 27 2023, from 9:00 to 15:00 NZST (Figure 6.19). Although additional observation days were desirable, limitations imposed by the PI's teaching and related responsibilities precluded this. To supplement scheduled observations, the PI conducted brief, randomised

half-hour spot checks throughout the cognitive assessment period, noting window positions during these visits. This strategy facilitated data collection within the PI's existing schedule.

The status of the doors and windows was observed at 20 minute intervals to assess the airing of the classroom. Meteorological conditions were recorded, with data from the local North Shore station managed by NIWA (NIWA, 2023b). Indoor temperature, RH, and CO₂ levels were monitored using the Massey University IEM device (Y. Wang et al., 2018; Weyers et al., 2017).

FIGURE 6.15: *Site Map of School and Location and Study Classrooms*



The images in **Figures** 6.16 and 6.17 are from the 1st day of observations. **Figure** 6.16 shows the front of S1-1 and S1-2 - it is evident that the front doors are open, the louvres are wide open, and most of the casement windows are partially or fully open. However, the sky is overcast. These photos were taken shortly after school started at 09:00, when the RH was approximately 96%.

FIGURE 6.16: North Front Elevation of S1-1 and S1-2



As demonstrated in Chapter 5, the CO₂ levels in School 1 remained consistently below 1000 ppm, which is a notable improvement compared to the findings of previous field studies. The PI attributes this success in School 1 to the louvre windows on the North facade of the classrooms, visible in **Figure 6.16**. These louvre windows enable classrooms to have some degree of air leakage, even when the windows are closed. In contrast, the classrooms in the earlier studies, which lacked louvre windows, were more "airtight" and did not have the same capability for natural ventilation.

Figure 6.17 depicts the south-facing (rear) windows of S1-1 and S1-2 taken shortly after the previous image. As shown, all the windows above are open, while the windows below are fixed glazed panels that cannot be opened.

FIGURE 6.17: *South Back Elevation of S1-1 and S1-2*



The image in **Figure 6.18** is from the 3rd day of observations. **Figure 6.18** shows the front of S1-5 and S1-6 - even on such a clear day, it is evident that even though the front doors are open, the louvres and front casement windows are closed.

FIGURE 6.18: North Front Elevation of S1-1 and S1-2



6.2.1 Results of observation study

Figure 6.19 illustrates the air temperature, RH, and the inter-climate conditions during the seven-day observation period. This can be read in conjunction with **Table 6.6**, which summarises the IEM data from the S1-1 and S1-2 classrooms, comparing these indoor and outdoor conditions over the three-day observation period.

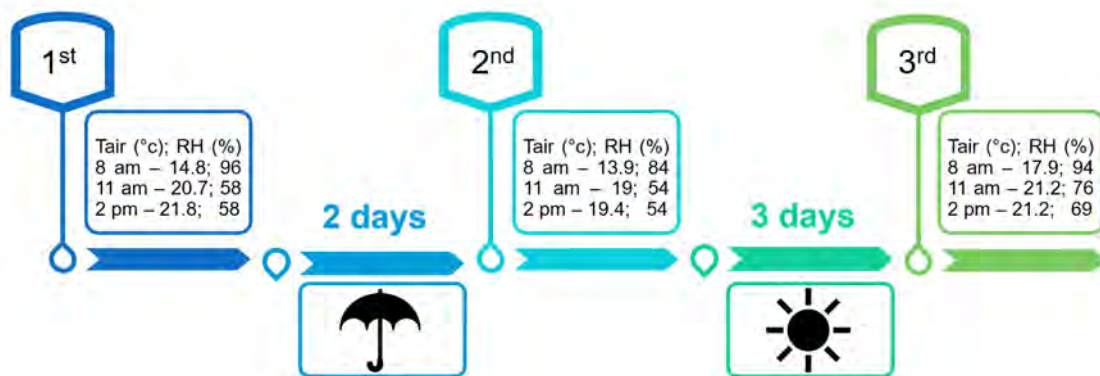
TABLE 6.6: Comparison of Classroom Indoor Environmental Conditions for Three Days (9am - 3pm)

		S1-1 IEM			S1-2 IEM			Outdoor variables		
		Temp (°C)	RH (%)	CO ₂ (ppm)	Temp (°C)	RH (%)	CO ₂ (ppm)	T _{out} (°C)	RH _{out} (%)	Windspeed (km/hr)
Min	Day 1	19.2 [1.1]	54 [5]	410 [76]	19.5 [1.8]	48 [3]	410 [168]	18.8	58	1.4
	Day 2	17.7 [0.8]	52 [3]	405 [65]	17.7 [1.8]	48 [4]	417 [55]	13.9	54	1.0
	Day 3	21.1 [0.9]	58 [4]	417 [74]	21.7 [1.0]	56 [4]	414 [71]	17.9	69	1.1
Max	Day 1	23.9 [1.1]	70 [4]	904 [77]	26.9 [1.8]	66 [3]	1000 [168]	21.8	96	5.0
	Day 2	21.9 [0.8]	66 [4]	631 [66]	24.8 [1.8]	63 [5]	769 [55]	19.4	84	8.3
	Day 3	24.9 [0.9]	75 [5]	701 [74]	25.8 [1.0]	73 [4]	718 [71]	21.2	94	6.5

The prospect of rain overshadowed the initial day of observation. 11.4 mm and 5.4 mm of rain fell over the next two days, respectively (NIWA, 2023b). Evidence of the impending rainfall is seen in the window closure after the first day (**Figure 6.19**), a precaution not deemed necessary on the subsequent days as conditions improved. There was no rain on the second day of observations, even with an 84% RH and the dry, sunny spell extended over the following three days, and in a similar pattern,

the third day of observation enjoyed clear skies. Rain was recorded after the third day of observations. These wetter conditions align with the high RH measurements recorded at 96% (**Figure 6.19**) on day one and 94% on day three (NIWA, 2023b). A gradual increase in temperature each day contributed to the need to open windows. Meanwhile, the wind speed remained below 10 km / h, which was conducive to opening and keeping windows open for extended periods.

FIGURE 6.19: Air Temperature and Relative Humidity for Three Observation Days



The temperature data (Tair in °C) presented in **Figure 6.19** indicates that the indoor temperature is relatively consistent over the three days, fluctuating between approximately 14 °C and 21 °C. The temperature exhibits diurnal variations, starting lower in the mornings at around 8:00 and gradually increasing throughout the day, reaching peak values around 11:00 or 14:00. In general, indoor temperatures remain within a comfortable range for classroom settings, avoiding extreme cold or heat.

The RH data reveal fluctuations throughout the day, typically showing a decline from morning to afternoon. Higher humidity levels are observed in the mornings around 8:00 a.m., reaching almost 100%. By 14:00, humidity levels drop to approximately 60-70%, indicating a significant drop as the day progresses.

windspeeds remain very low throughout the observation period, indicating minimal ventilation from outdoor breezes.

In summary, since the indoor temperature is generally comfortable, teachers might not feel a strong need to open the windows solely to control the temperature. However, windows could be opened when the temperature approaches the upper

end of the spectrum (late morning to early afternoon) to prevent the room from becoming too warm. With RH peaking in the mornings, teachers might open the windows early to reduce dampness and introduce drier air. As humidity levels drop in the afternoon, the need to open windows for humidity control diminishes. With the indoor windspeed consistently low, natural ventilation is minimal. Teachers can open windows to improve air circulation and freshness, regardless of time of day, especially when the classrooms are full, and CO₂ levels might increase.

At the beginning of the project, an inspection of all doors and windows confirmed their operational status. A detailed survey was then performed, collecting information on various features of the window. This survey documented the number and total area of the windows (m²), the types of windows, the minimum height of the windowsills (measured from the ground in metres) and the mechanisms used to open them. The details of these findings are presented in **Table 6.7**.

TABLE 6.7: *An Overview of the Window Features of the Classroom and Library and their Controls*

		Window Design					Window Operation
	Area (m ²)	WA ¹ (m ²)	NW ²	Window Type	MW ³	Ventilation	
Classrooms (S0R1 – S0R6)	66	3.36	1	Louvre (North)	Above head height	Double-sided at 2 levels + louvre opening	Manually with handle
		7.20	6	Side-hung outward opening (North)	0.64		Manually
		2.50	4	Top-hung outward opening (South)	1.50		Manually with handle
Library (S0R7)	175	3.36	1	Louvre (North)	Above head height	Double-sided at 2 levels + louvre opening	Manually with handle
		3.60	3	Side-hung outward opening (North)	0.64		Manually
		4.90	6	Top-hung outward opening (South)	1.00		Manually
		2.50	4	Top-hung outward opening (South)	1.50		Manually

1 = Total window area (m²) in each classroom

2 = Number of windows

3 = Minimum height of windowsill (m)

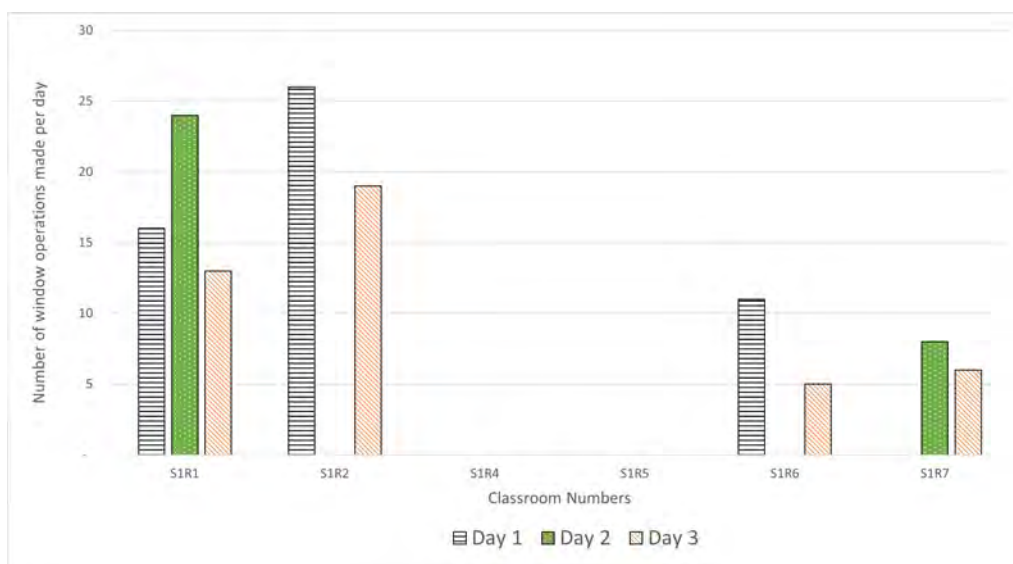
Table 6.7 outlines the features of the window in specific areas, including classrooms and a library. For classrooms (S1-1 to S1-6), with an area of 66 m², the window types include louvres in the north, side-hung outward openings in the north, and top-hung outward openings in the south. These windows are manually operated with handles

that provide double-sided ventilation at two levels, enhanced by louvre openings. Specific details include a total window area of 3.36 m² for louvres, 7.20 m² for six side-hung windows with a minimum height of 0.64 m, and 2.50 m² for four top-hung windows with a minimum height of 1.50 m.

The library (S1-7), with an area of 175 m², features similar window types and ventilation methods, also operated manually. It consists of 3.36 m² of louvres, 3.60 m² for three side-hung windows with a minimum height of 0.64 m, 4.90 m² for six top-hung windows with a minimum height of 1.00 m, and 2.50 m² for four top-hung windows with a minimum height of 1.50 m.

The external doors were unlocked and propped open by the school caretaker prior to beginning classes. **Figure 6.20** illustrates the frequency of window adjustments in each classroom during the study period. Window manipulation typically began with the arrival of teachers, usually around 8:30 am. These early morning adjustments, mainly for ventilation purposes before students entered the classrooms, constituted 43% of all recorded window operations.

FIGURE 6.20: *Window Operation Frequency in Different Classrooms Over Three Days*



The windows were not closed due to rain or wind. In classroom S1-2, 10% of the instances where the windows were closed were in response to noise disruptions, particularly during swim time at the nearby pool (**Figure 6.21**, far right image).

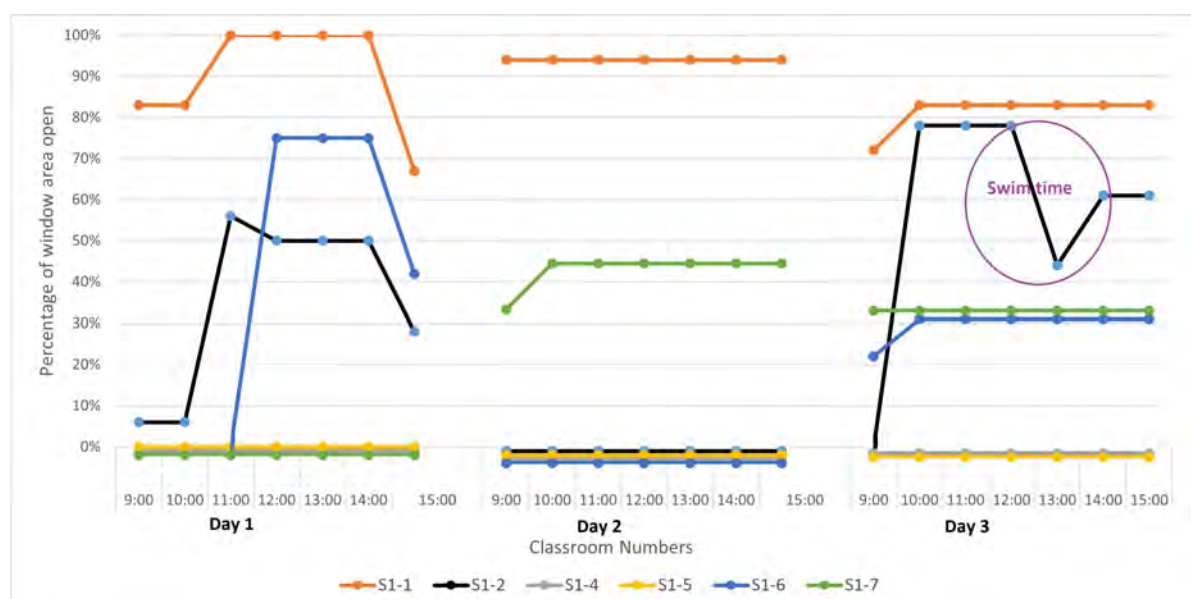
Generally, windows remained open unless closed due to noise or adverse weather. The remaining window operations were due to on-arrival (43%) or closing-up (9%) activities.

In summary, the reasons why the windows were operated for three days can be reported as follows:

On arrival = 43%	Noise = 10%
Closing up = 9%	Wind = 0%
IEQ issues = 38%	Rain = 0%

Figure 6.21 illustrates the percentage of open window opening areas in each room. This is based on the open window area available and the frequency with which the windows were operated every hour.

FIGURE 6.21: *Percentage of Window Area that is Open Over the School Day (by Class) During the Observation Study.*



The data reflect a variety of school practices in relation to censorship. Throughout the observation period, the north-facing front doors of all classrooms remained open. The behaviour in S1-1 and S1-2 demonstrated consistent window opening, contributing to adequate ventilation. In contrast, the windows in S1-4 were generally kept closed. The teacher was unavailable for comment. S1-5 and S1-6, which share a

space with a partition and often function as a single teaching area (S1-5), showed variable window and door usage, possibly due to the team teaching approach in this space. The classroom was divided into two cohorts at the beginning of the 2024 teaching year and the partition closed.

Compared to the 2015 Auckland survey, the average duration of window opening in this school during the observation period corresponds to 30%, which is 10% lower than the pre-COVID-19 teacher survey.

A Spearman correlation tested the relationship between the open window area (WOA in m^2) and environmental factors to analyse the usage of the window in reaction to IEQ (stuffy environment, TC). With visual data indicating 38% of window operations tied to IEQ, variables such as indoor / outdoor temperature, humidity, CO_2 levels, and wind speed correlated with WOA. Operations not related to the environment, such as end-of-day closures, were omitted from this analysis. Spearman's correlations confirm significant links: a strong positive correlation between open window area and indoor temperature ($\rho = 0.758$, $p < 0.018$) and a notable positive correlation with outdoor temperature ($\rho = 0.893$, $p = 0.001$). However, an inverse, but not significant, relationship was observed with the levels of RH ($\rho = -0.341$, $p = 0.370$), and CO_2 ($\rho = -0.613$, $p = 0.079$) were noted.

The contrast in window opening routines between classrooms within one school (S1-1/S1-2 compared to S1-4) considering post-COVID-19 guidelines is striking, indicating a significant divergence despite receiving the same school-wide information from the principal. This outcome highlights that window-opening practices are predominantly driven by individual choices influenced by external factors such as temperature. These relationships emphasise the impact of window operation on indoor climate and air quality.

Although observation of window-opening behaviours in primary schools provides valuable insight into how airing is used in educational environments, these manual observations can often be limited by their subjective nature and the intensive labour required. To enhance the accuracy and efficiency of data collection, the implementation of magnetic sensors in doors and windows offers a promising technological advancement. Using these sensors, it becomes possible to continuously monitor the opening and closing behaviours of windows and doors. This shift

improves data granularity and reliability and enables long-term studies with minimal human intervention, providing a more comprehensive understanding of their impact on TC&V in primary school settings.

6.2.2 Summary and possible implications

The study examined window operation patterns in a school setting for seven days, considering various environmental factors such as temperature, RH, and weather conditions. The findings revealed that teachers primarily initiated window operations upon arrival, primarily for ventilation, before students entered. IEQ prompted 38% for window adjustments, while external factors such as noise and weather also influenced window operations. Despite shared school-wide guidelines, the study observed significant variations in window-opening practices in different classrooms. Statistical analysis showed strong positive correlations between open window areas and indoor and outdoor temperatures, while negative correlations with levels of RH and CO₂ were observed.

1. **Individualized approach to ventilation:** The stark differences in window operation practices between classrooms suggest that a one-size-fits-all approach to ventilation guidelines may not be effective. Schools may need to develop more tailored strategies for individual teacher preferences and classroom-specific factors.
2. **Environmental awareness training:** Given the strong correlation between window operations and environmental factors, teachers may need enhanced training in optimal ventilation practices based on various environmental conditions.
3. **Automated systems consideration:** Inconsistency in manual window operations might indicate a potential benefit in implementing automated or semi-automated ventilation systems that respond to environmental data.
4. **Health and comfort impacts:** The varied practices could lead to differences in IAQ and TC between classrooms, potentially affecting student health, comfort, and performance.
5. **Energy efficiency:** Inconsistent window operation practices could affect the overall energy efficiency of the school. This might call for a more standardised approach or the integration of smart building technologies.

6. **Policy development:** The findings could inform the development of more nuanced school ventilation policies, particularly in the post-COVID-19 guidelines.
7. **Further research needs:** The study highlights the need for more extensive research into the long-term effects of different ventilation practices on IEQ, student performance, and energy consumption in educational settings.

Building on the previous examination of observation data, the next section will examine the implementation and effectiveness of window and door sensors in monitoring classroom ventilation practices.

To avoid repetition, the discussion section of this observational study has been integrated with the discussion of window and door mechanisms.

6.3 Window and door sensors results

This study section aims to detail airing behaviour in a primary school environment through window sensor monitoring techniques and data analysis to address research question 2b.

6.3.1 Response rate

Initially, sensors were installed in all classrooms (S1-1 to S1-6), but frequent power failures and data errors led to a focus on the three classrooms (S1-1, S1-2, and S1-3) where cognitive tests were conducted.

Eight sensors were installed in S1-1 and S1-3, while S1-2 had six sensors due to a louvre window not closing tightly. Each classroom had two door sensors, with S1-1 having an additional sensor because of its inter-leading door to S1-2. The remaining sensors were placed on the windows. The recordings are logged every 5 seconds.

Details of data collection timing can be found in **Appendix D**.

6.3.2 Validation of the sensors with observations

The validation method of the sensors was described in **Section 4.3.4**.

At the end of 2023, an observation study detected anomalies due to battery depletion in many sensors, causing device malfunctions and unreliable data. To address this, the PI returned the next day with replacement batteries to restore the validity of the study.

This incident highlighted the need for regular maintenance of the equipment and exposed vulnerabilities in long-term field studies. Consequently, a stricter battery replacement schedule was implemented, turning a potential setback into a methodological improvement.

Integrating systematic observation with magnetic sensor installation in a school provided a comprehensive understanding of human interaction, building use, and TC. This approach, which captured quantitative and qualitative data, enhanced insights into ventilation practices and adaptive behaviours beyond what sensor data alone could reveal.

6.3.3 Results of teacher behaviour in the same teaching space

In this study, the PI presents a comparative survey of window behaviour between two teachers in the same venue: Teacher One in S1-1 in 2023 and Teacher Two in 2014. By analysing S1-1 during these periods, the PI aims to compare the window-opening behaviours of these two teachers of similar age.

In the middle of Term 1, 2023, S1-2 was transferred to another classroom equipped with an inverter heat pump, while S1-3 was relocated to the library during the same year. Subsequently, remediation work occurred in these classrooms throughout 2023, making direct comparisons with S1-1 in 2023 unfeasible. Furthermore, due to insufficient and inconsistent data availability during Term 1 and Term 2 in 2024, conducting a comparative analysis between the remaining classrooms was not feasible.

Comparative analysis of classroom dynamics in S1-1 (2023 vs 2024)

Details of the meteorological conditions (mean and [SD]) for the period under review can be found in **Table E.2** in **Appendix E**. These figures provide a detailed representation of weather patterns, temperature variations, precipitation levels, and windspeeds over the specified terms. The specific dates can be referenced in **Tables D.3** and **D.5**. This focused review will allow an understanding of the meteorological anomalies and trends relevant to these two terms.

Similar meteorological conditions need to be identified to compare two different teachers who occupy the same space over two years. Analysis of the data in **Tables 6.8** and **6.9** revealed that Week 7 in Term 1 and Week 5 in Term 2 exhibited the most consistent conditions throughout the years.

TABLE 6.8: Comparison of meteorological conditions for selected weeks in Auckland Term One 2023 and 2024

2023				
Term One Weeks	Temp (°C) Mean[SD]	RH (%) Mean[SD]	Rainfall (mm) Mean[SD]	Windspeed (kph) Mean[SD]
5	19.2 [0.1]	85 [3]	0.9 [1.6]	22.6 [2.5]
6	18.9 [0.8]	80 [2]	1.0 [1.3]	25.3 [3.5]
7	18.4 [1.4]	78 [9]	2.0 [3.1]	26.7 [5.6]
8	16.5 [0.7]	78 [6]	3.8 [6.8]	22.6 [6.0]
9	16.0 [2.0]	76 [9]	0.4 [0.5]	23.3 [7.0]
10	16.4 [1.3]	79 [6]	2.0 [2.4]	27.0 [8.9]

2024				
Term One Weeks	Temp (°C) Mean[SD]	RH (%) Mean[SD]	Rainfall (mm) Mean[SD]	Windspeed (kph) Mean[SD]
5	19.5 [0.4]	78 [6]	2.9 [3.7]	27.1 [5.1]
6	18.3 [1.3]	74 [8]	2.8 [3.8]	32.6 [6.7]
7	18.9 [0.9]	86 [5]	2.9 [3.7]	25.6 [6.2]
8	15.6 [0.9]	69 [5]	0.1 [0.1]	23.3 [5.4]
9	18.3 [1.2]	77 [4]	1.1 [0.7]	37.1 [3.0]
10	17.1 [0.7]	77 [3]	0.8 [1.6]	18.1 [5.1]

These weeks will be used for this analysis. These selected weeks provide a balanced representation of the conditions in both years, allowing for a more accurate comparison of teaching practices while minimising the impact of environmental variations.

TABLE 6.9: Comparison of meteorological conditions for selected weeks in Auckland Term Two 2023 and 2024

2023				
Term Two Weeks	Temp (°C) Mean[SD]	RH (%) Mean[SD]	Rainfall (mm) Mean[SD]	Windspeed (kph) Mean[SD]
5	13.7 [1.6]	86 [4]	4.7 [8.8]	24.1 [10.1]
6	15.6 [1.2]	89 [4]	3.0 [5.0]	28.2 [9.3]
7	11.9 [0.4]	79 [4]	1.1 [1.5]	24.9 [3.0]
8	10.5 [1.2]	85 [4]	1.3 [2.4]	21.9 [5.9]
9	12.9 [0.9]	90 [2]	6.7 [6.2]	22.3 [6.0]

2024				
Term Two Weeks	Temp (°C) Mean[SD]	RH (%) Mean[SD]	Rainfall (mm) Mean[SD]	Windspeed (kph) Mean[SD]
5	13.4 [0.8]	82 [4]	5.8 [6.5]	36.7 [13.5]
6	13.5 [0.9]	82 [6]	0.2 [0.5]	20.7 [4.0]
7	14.4 [1.6]	85 [5]	11.8 [15.1]	27.7 [7.7]
8	12.8 [1.1]	84 [4]	4.5[8.1]	22.6 [3.4]
9	12.2 [1.5]	87 [8]	0.5 [0.5]	34.7 [17.9]

Window status

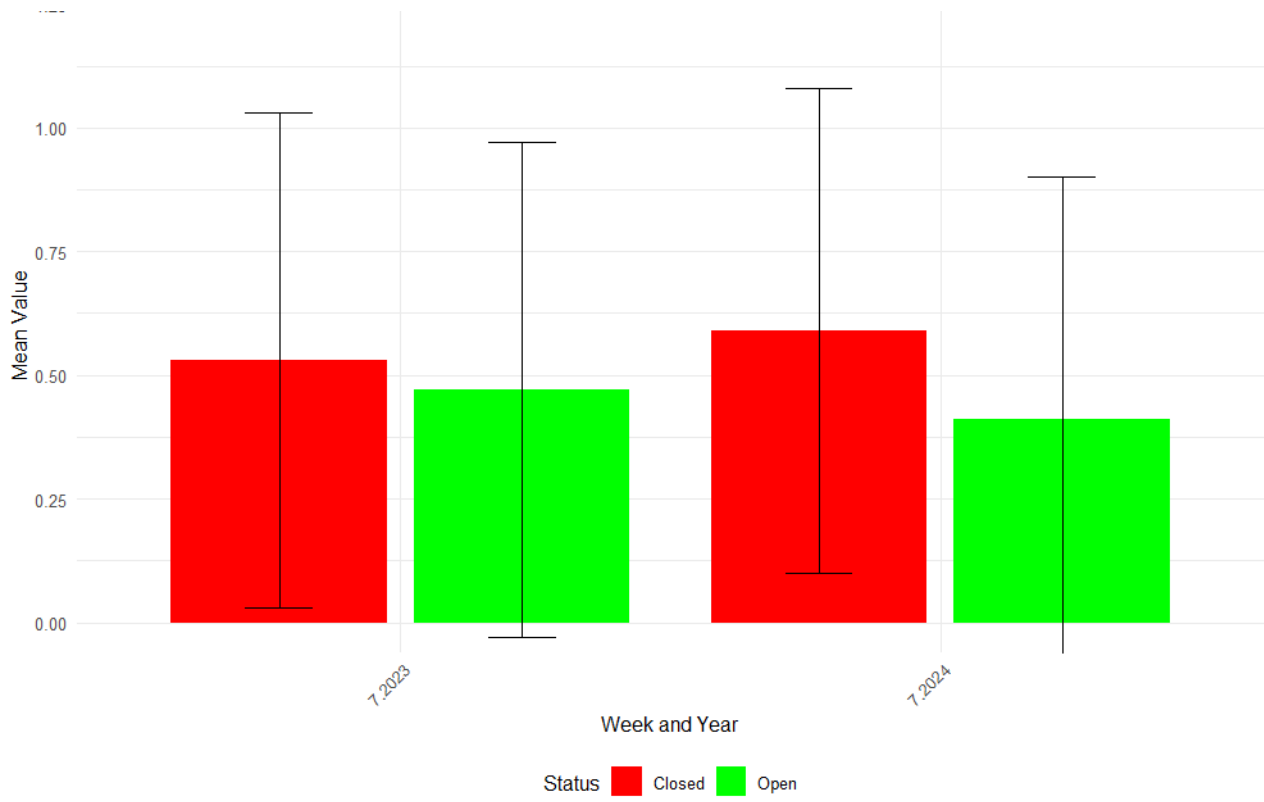
Table 6.10 represents the percentage of time that specific sensors are open throughout the week for each study period (09:00-15:00, Monday to Friday).

TABLE 6.10: Window Sensor Open/Close Durations by Study Period - Term 1 (Summer) and Term 2 (Autumn)

Term	Week	Season	2023		2024	
			Mean [SD] Open	Mean [SD] Closed	Mean [SD] Open	Mean [SD] Closed
1	7	Summer	0.47 [0.50]	0.53 [0.50]	0.41 [0.49]	0.59 [0.49]
2	5	Autumn	0.59 [0.49]	0.41 [0.49]	0.23 [0.42]	0.77 [0.42]

Based on this information, Figures 6.22 and 6.23 represent the comparison of the selected mean [SD] values for sensor status during the study (09:00-15:00, Monday to Friday).

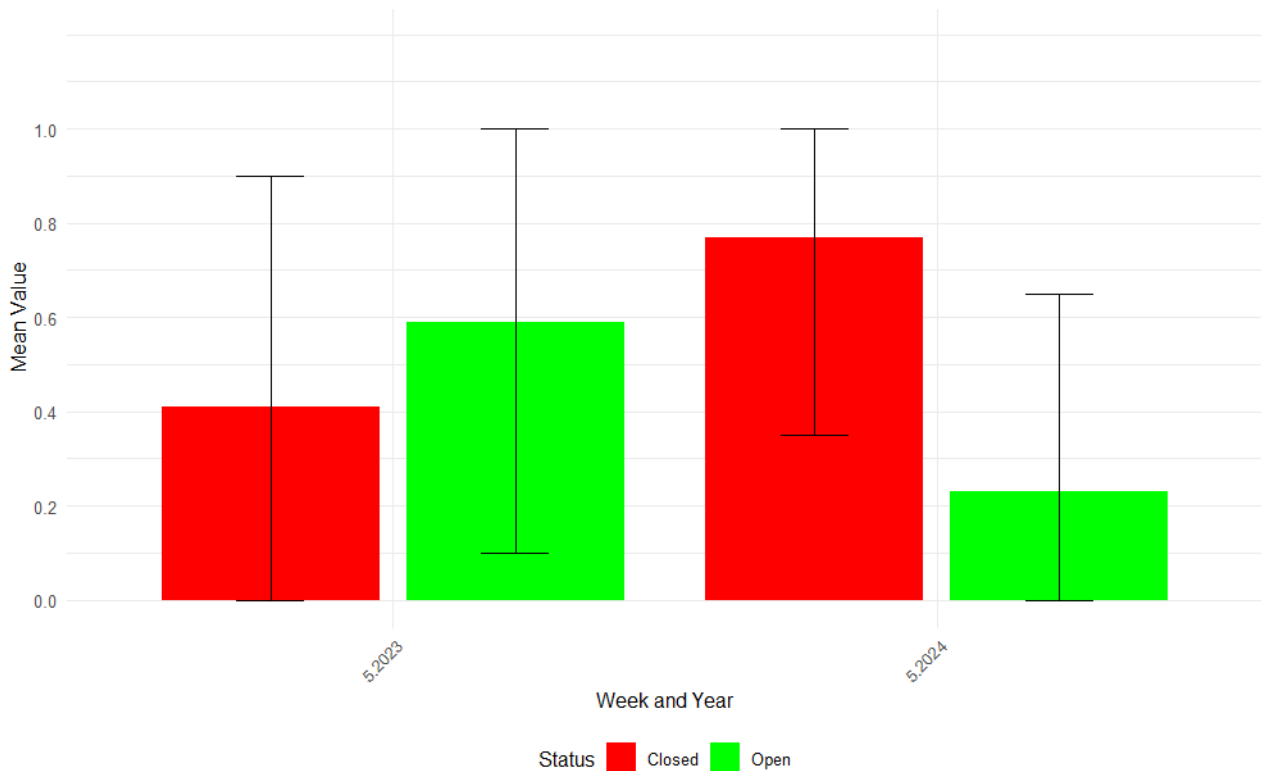
FIGURE 6.22: Comparison of Mean Values for Closed and Open Status Over Time (Week 7)



Based on the data provided (Figure 6.22), it appears that the behaviour of the window varies slightly between the open and closed states for Teacher 1 and Teacher 2 during Week 7 of the summer season. There is noticeable consistency in the data across both years in terms of standard deviation, indicating similar variability in window behaviour. The mean values suggest a slight trend that the windows tend to be closed more often than open, with the tendency being more pronounced for Teacher 2.

In conclusion, **the data indicate a preference for keeping windows closed in both years, which is becoming slightly stronger for Teacher 2.** The variability in the data remains consistent between the open and closed states throughout both years.

FIGURE 6.23: Comparison of Mean Values for Closed and Open Status Over Time (Week 5)



The change in window behaviour (**Figure 6.23**) from Teacher 1 to Teacher 2 is apparent and significant. For Teacher 1, the preference leaned towards keeping windows open during autumn Week 5, as indicated by the higher mean value for open windows. However, the data for Teacher 2 show a strong inclination towards closed windows, with the mean value for closed states being significantly higher than for open states. This shift signifies a notable change in behaviour or possibly external factors that influence the decision to keep windows closed more frequently.

The variability in window behaviour, as reflected in the standard deviations, was consistent for each teacher but slightly reduced for Teacher 2. The identical standard deviations for open and closed windows in each respective year suggest a similar spread around the mean values. However, the slight reduction in variability for Teacher 2 indicates more consistent behaviour, possibly reflecting a stronger

adherence to the preference for closed windows.

During autumn Week 5 for Teacher 1, there was a clear preference for open windows, with a mean of 0.59 compared to 0.41 for closed windows. Conversely, autumn Week 5 for Teacher 2 demonstrated a strong preference for closed windows, with a mean of 0.77 versus 0.23 for open windows. This shift indicates a significant behavioural change towards favouring closed windows for Teacher 2.

This data demonstrates different window behaviour patterns between teachers using the same space under similar meteorological conditions.

Ultimately, this analysis reveals a considerable change in behaviour between the two teachers, with Teacher 2 favouring closed windows more consistently than Teacher 1. This could suggest differences in teaching preference, pedagogical strategies, or possibly external factors that influence the decision to keep windows closed more frequently when Teacher 2 uses the space.

Considering data over an extended period, it is clear that, regardless of external conditions, Teacher 2 consistently prefers to keep the windows closed. This behaviour is evident across various time frames, highlighting a strong inclination toward maintaining closed windows regardless of the external meteorological conditions.

Figure 6.24 and **Figure 6.25** represent the percentage of time that specific sensors are open throughout the week, broken down by individual days (Monday to Friday).

FIGURE 6.24: *Daily Sensor Activity: Percentage Time Open by Day of the Week (Term One 2023) - Teacher One*

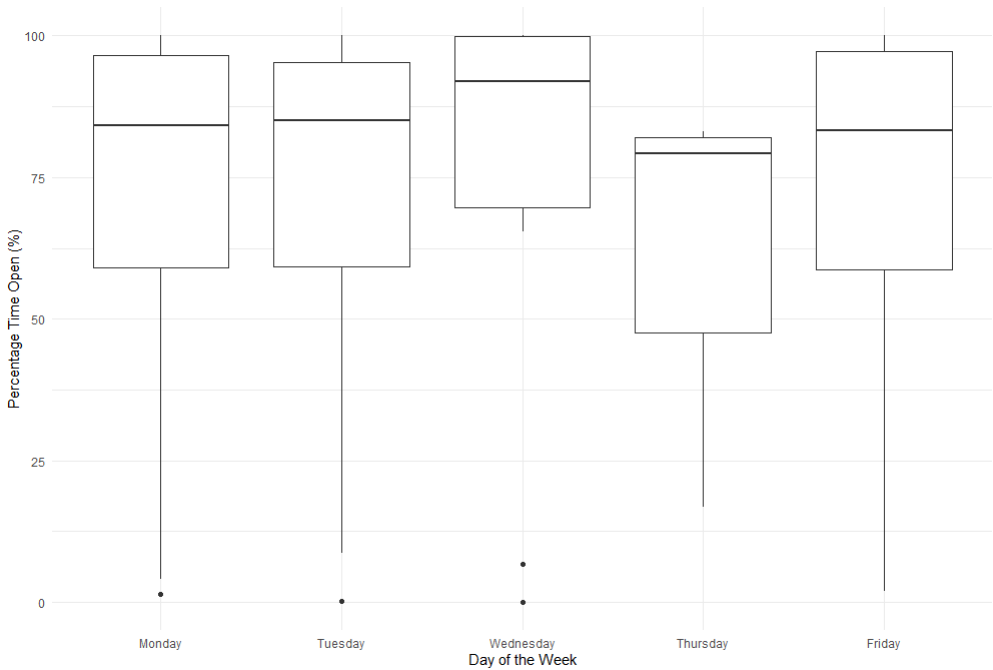
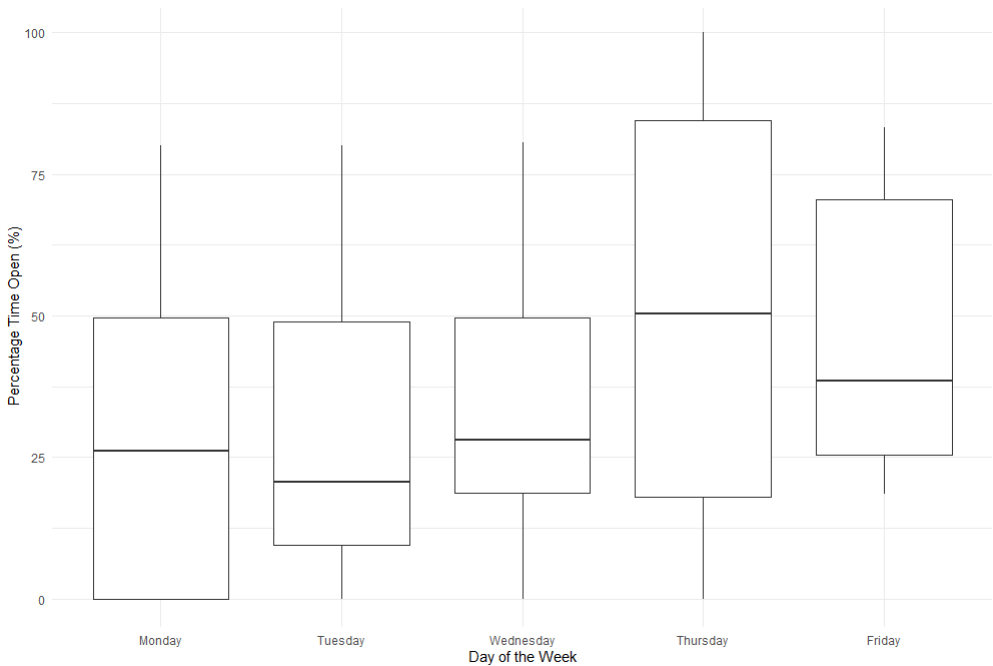


FIGURE 6.25: *Daily Sensor Activity: Percentage Time Open by Day of the Week (Term One 2024) - Teacher Two*



The following can be derived from **Figures 6.24 and 6.25** regarding S1-1 teachers during Term 1 (2023 vs 2024):

1. Teacher One

- Generally, windows are open for a longer period throughout the week, with medians around 75% or higher most days.
- Shows a consistent pattern with similar medians on Monday, Tuesday, Wednesday, and Friday.
- Thursday is an outlier where the median decreases significantly to around 50%, indicating irregular airing that day.

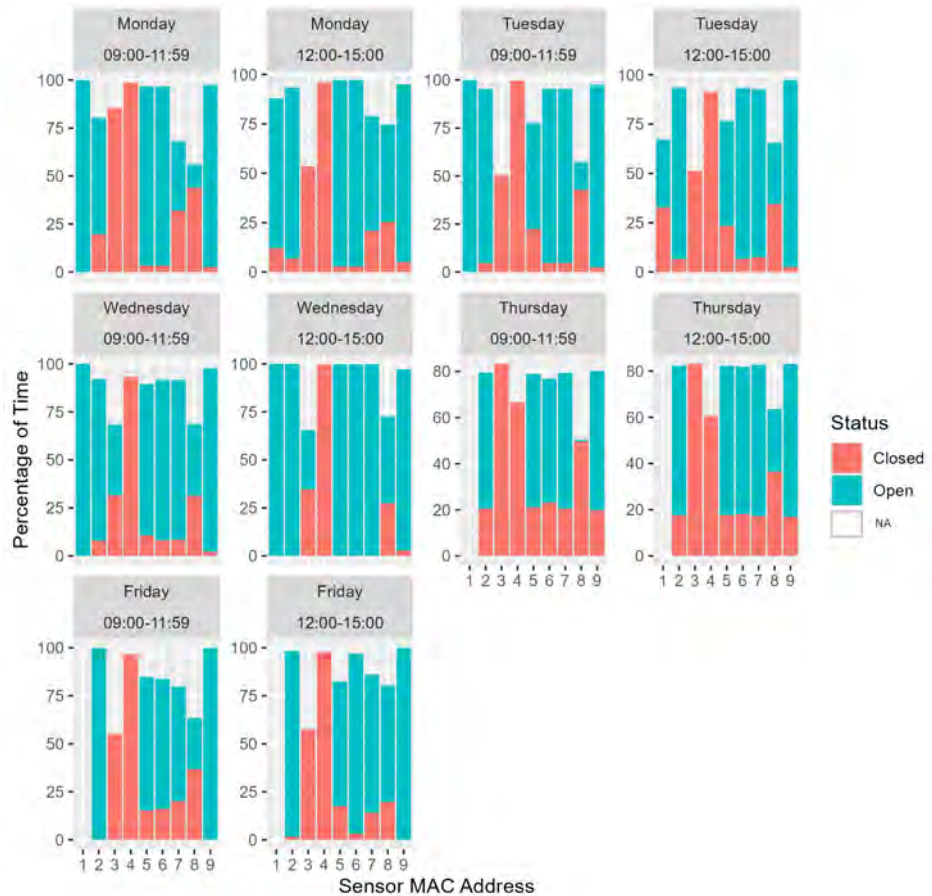
2. Teacher Two

- Teacher 2 has lower median values, particularly on Monday, Tuesday and Friday, where the median is around 25% to 30%.
- On Thursday, Teacher 2 shows a wide range of times the sensor is open, with the median around 50% but with substantial variation.
- Teacher 2's airing behaviour is more variable and less consistent than Teacher 1, showing more fluctuations in the percentage time open across the days.

In summary, Teacher 1 tends to air out the classroom more consistently and for longer periods on most days compared to Teacher 2, who shows more variability and generally keeps the windows open for shorter periods. This suggests that Teacher 1 might prioritize ventilation more regularly than Teacher 2.

Figure 6.26 shows the weekly open / closed status analysis for Teacher 1, 2023.

FIGURE 6.26: Six Week Analysis of Window Open/Closed Status for S1-1 by Time Intervals (Term One 2023) - Teacher One



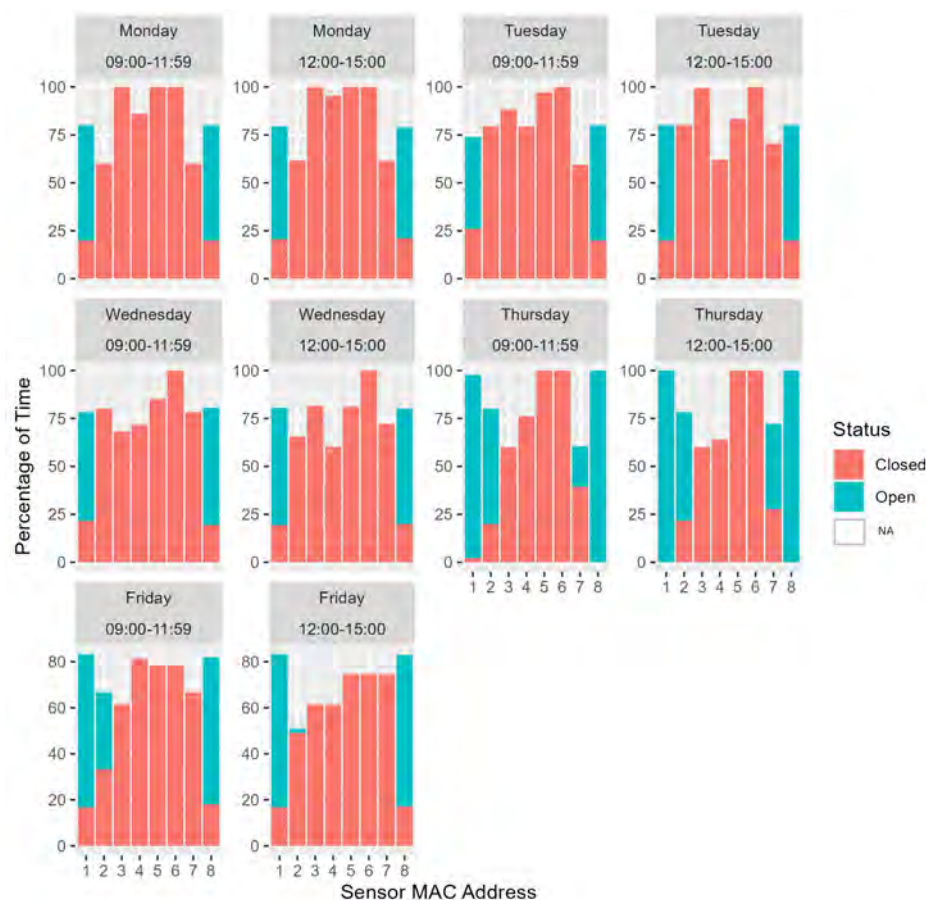
The weekly analysis of the open/closed status of the window for S1-1 (**Figure 6.26**) illustrates the percentage of time the windows were open or closed during the selected weeks. The analysis spans multiple days, from Monday to Friday, covering distinct time slots from 09:00-11:59 and 12:00-15:00. Each bar in the graphs represents the data recorded by the sensor, identified by its MAC address (1-8). The blue segments denote the proportion of time windows that were open, while the red segments indicate the percentage of time they were closed. This visualisation provides insights into airflow patterns within the monitored environment, helping to better understand airflow and potential areas for improvement in IEQ management. Due to power failures, data collection was inconsistent, as evident in the blank columns or when the y-axis does not equate to 100%.

Based on **Figure 6.26** two sensors (#3 and #4) are more frequently closed. Sensor #3 was installed on the window behind the teacher's desk, which was kept closed

due to drafts, and sensor #4 was fixed to the door connecting S1-1 and S1-2. This interconnecting door was mostly kept closed and only used during co-teaching events. Sensor #1 stopped working after some time, but was reconnected in term 2, 2023. Upon investigation, it was found that sensor #1 was originally attached to the front door of the classroom, which had been dislodged.

Figure 6.27 shows the weekly open / closed status analysis for Teacher 2, 2024.

FIGURE 6.27: *Six Week Analysis of Window Open/Closed Status for S1-1 by Time Intervals (Term One 2024) - Teacher Two*



From the provided data (**Figures 6.26**) and 6.27), the following inferences can be made:

1. **General airing behaviour trend** - Teacher 1 keeps the windows open more often than Teacher 2. This is evident as the mean percentage of time the windows are open is generally higher in 2023 compared to 2024.
2. Week-by-week analysis

- **Week 5:** In 2023, the windows were open 70% of the time on average, while in 2024 it increased to 85%. However, the standard deviation (SD) indicates a more consistent airing in 2024.
- **Week 6:** The windows were open 68% of the time in 2023 but significantly less in 2024 at 52%.
- **Week 7:** In 2023, the windows were open 61% of the time, while they were 41% in 2024, indicating less airing activity in 2024.
- **Week 8:** There is a drop in window opening from 83% in 2023 to 32% in 2024.
- **Week 9:** The windows were open 77% of the time in 2023 compared to 37% in 2024.
- **Week 10:** Similarly, there is a decline from 66% open time in 2023 to 27% in 2024.

3. Seasonal transition

- During the autumn (Week 7), there is a notable change in behaviour.
 - In 2023, 61% of the time the windows were open and 39% closed.
 - In 2024, a shift is observed with only 41% of the time open and 59% closed.

4. The **standard deviations** are generally consistent across both years, indicating varying degrees of airing behaviour by both teachers but generally uniform within their year.

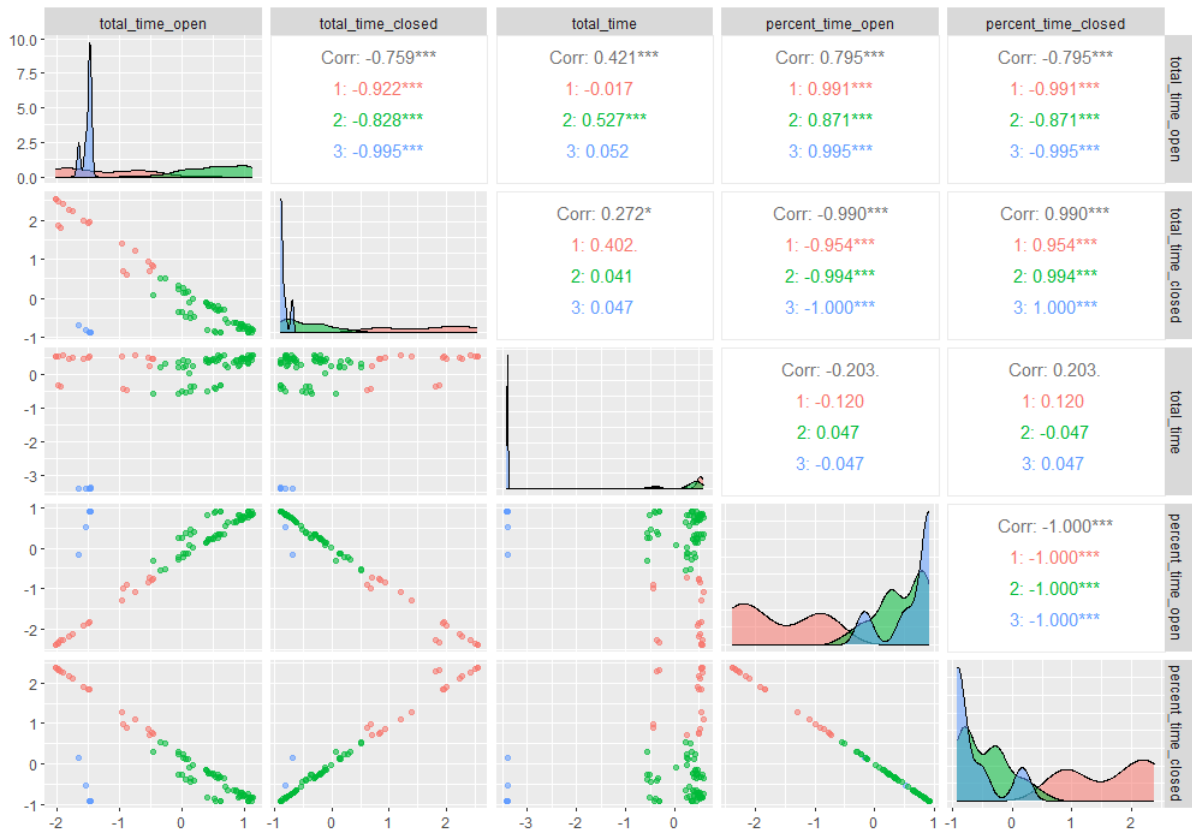
Teacher 1 consistently keeps the windows open for more time in all weeks compared to Teacher 2. Teacher 2 demonstrates fluctuating behaviour with a notable decrease in the window open time, especially in the later weeks (Weeks 7-10, 2024), corresponding to the autumn season. This suggests that Teacher 1 prefers to air more frequently, whereas Teacher 2 might have different environmental preferences or constraints that result in less frequent window openings.

The previous analysis is supported by the results of the following two pair plots (**Figure 6.28 and 6.29**). Scatterplot matrices, also known as pair plots, are a powerful visualisation tool used in data analysis to explore pairwise relationships between

multiple variables simultaneously. Additionally, including linear fit lines and numerical correlation values enhances the analytic depth, providing immediate insights into the strength and direction of relationships between variables. **Green** symbolises high-frequency use sensors, red represents moderate-frequency usage sensors, and blue indicates low-frequency usage sensors.

Several key differences and patterns can be noticed in the airing behaviour of the two teachers in S1-1. **Figure 6.28** needs to be read in conjunction with the previous **Section** discussion for **Figure 6.26**.

FIGURE 6.28: S1-1 Scatterplot Matrix with Density Plots and Correlation Coefficients for Time Variables (Term 1 2023) - Teacher One



Note: Green symbolises high-frequency use sensors, red represents moderate-frequency usage sensors, and blue indicates low-frequency usage sensors

Teacher 1 - Term One, 2023 - Figure 6.28

1. **Window open time:** density plots show a concentrated peak around a specific time, suggesting more consistent durations for window opening.

2. Data points are more dispersed and show more variability in behaviour, suggesting more random or situational window-opening behaviour.

Figure 6.29 needs to be read in conjunction with the the previous Section discussion for Figure 6.27.

FIGURE 6.29: *S1-1 Scatterplot Matrix with Density Plots and Correlation Coefficients for Time Variables (Term 1 2024) - Teacher Two*



Note: Green symbolises high-frequency use sensors, red represents moderate-frequency usage sensors, and blue indicates low-frequency usage sensors

Teacher 2 - Term One, 2024 - Figure 6.29

1. **Window open time:** There are multiple peaks in the density plot, indicating that window opening times vary more widely.
2. The data points exhibit strong linearity, indicating a consistent behavioural pattern.

Significant distinguishing factors:

1. Consistency

- **Teacher 1** exhibits more variability and less consistency with narrow peaks in the density plots.
- **Teacher 2** shows greater consistency and predictability in window opening/closing behaviour, as indicated by the strong correlations and distinct peaks of the density plots.

2. Correlation strength

- **Teacher 1** shows weaker correlations, suggesting more situational or less predictable behaviour.
- **Teacher 2** has generally stronger correlations (closer to -1 or 1), indicating a more homogenised behaviour.

3. Behavioural patterns

- **Teacher 1** might be experimenting more or making decisions based on more varied conditions.
- **Teacher 2's** behaviour indicates a more regimented and potentially environment-controlled approach to window management.

In conclusion, the most significant difference between the two teachers is the consistency and predictability of their window-opening behaviour. Teacher 2 maintains a more predictable and consistent pattern, while Teacher 1 displays more variability and spontaneity in their window management actions. This implies that Teacher 2 might follow a more routine-based approach, while Teacher 1 is likely more flexible or responsive to immediate environmental conditions.

Impact of meteorological conditions on airing behaviour

The following can be inferred from the previous discussion:

2023 vs 2024 Term One

- **Week 5**

- The temperature slightly increased from 19.1 °C to 19.4 °C.
- Humidity decreased from 84% to 78%.
- Rainfall increased significantly from 0.9 to 2.8 mm.
- Windspeed increased from 22.6 kph to 27.1 kph.
- 2023 Mean Open: 0.70 [0.46]
- 2024 Mean Open: 0.85 [0.35]
- The significant increase in window opening from 70% to 85% might correlate with lower humidity and higher windspeed, suggesting a more conducive environment for window opening. The slight increase in temperature could be a minor contributor. Higher rainfall does not seem to deter opening, possibly due to IAQ and ventilation priorities.

- **Week 6**

- The temperature slightly decreased from 18.9 °C to 18.6 °C.
- Humidity decreased from 80% to 75%.
- Rainfall increased from 0.9 mm to 2.8 mm.
- Windspeed increased from 25.2 kph to 28.1 kph.
- 2023 Mean Open: 0.68 [0.47]
- 2024 Mean Open: 0.52 [0.50]
- Despite weather parameters such as temperature and humidity showing slight decreases and windspeed increasing, the percentage of open windows decreased from 85% to 52%. This suggests that other factors, possibly higher cloud cover leading to a perception of colder weather or higher rainfall deterring window opening, might have influenced the behaviour.

Correlation analysis

The Pearson correlation coefficients between the percentage of window opening and key weather parameters for weeks 5 to 10 are displayed in **Table 6.11**.

TABLE 6.11: *Pearson Correlation Coefficient Between Window Opening and Key Weather Parameters Term One (2023-2024)*

Variable	Correlation with Window Opening
Temp Mean	+0.35
Relative Humidity	-0.45
Rainfall	-0.30
Windspeed	+0.50
Cloud Cover	-0.40

- Temperature shows a moderate positive correlation, suggesting that higher temperatures tend to increase window opening slightly.
- RH shows negative correlations, indicating higher humidity related to fewer open windows.
- Windspeed shows a strong positive correlation, suggesting higher windspeeds promote window opening.
- Rainfall has a negative correlation, although not as strong as humidity or cloud cover.

6.3.4 Window opening behaviour discussion

The literature supports various aspects of our findings related to IEQ and window-opening behaviours in primary school classrooms.

1. **Impact of weather conditions on ventilation and window-opening behaviour:** Studies like those by Fromme et al. (2008) and Diaz (2021) illustrate how weather factors such as temperature, humidity, and windspeed affect window-opening practices in classrooms. Colder weather reduces window openness to maintain indoor TC, while warmer weather and higher windspeeds encourage ventilation to manage temperature and air quality. This study showed that Teachers 1 and 2 adjusted their window-opening behaviours based

on weekly weather variations, with colder weeks saw reduced ventilation and warmer weeks facilitated more frequent window openings.

2. **Interplay between TC and IAQ:** Research by Wargocki and Wyon (2007a), (2007b) and Bakó-Biró et al. (2012) highlights that achieving optimal ventilation while maintaining TC is critical for sustaining an effective learning environment. Over-ventilation can lead to discomfort due to cold drafts, whereas under-ventilation can compromise air quality. This study identified that balancing ventilation (through window management) with maintaining suitable temperatures is challenging but essential. For example, across different weeks and terms, the need to open windows for ventilation often compromised TC, especially in colder seasons.
3. **Teacher and student health and cognitive performance:** The decline in window-opening behaviour (and thus ventilation) by Teacher 2 correlated with increased indoor CO₂ levels, potentially impacting student cognitive functions and overall health. Teacher 1's consistent window-opening practices helped maintain lower CO₂ levels and possibly better cognitive performance. This is supported by studies by Satish et al. (2012) and Allen et al. (2017) who demonstrate that higher indoor CO₂ levels, often due to inadequate ventilation, are linked to diminished cognitive performance and attentiveness among students. Additional research by Coleman et al. (2017) also supports the notion that optimal IAQ is crucial for maintaining student health and learning outcomes.
4. **Influence of architectural and structural features on IEQ:** Research by Zhang et al. (2016) and Bennett et al. (2019) points to the significant role of classroom design, including the size and accessibility of windows, in influencing ventilation practices and overall IEQ. Effective classroom designs facilitate better teacher control over environmental conditions, contributing to more consistent ventilation practices and better IAQ. The structure of classrooms, including the availability and accessibility of windows, played a crucial role in determining how often and effectively teachers could manage ventilation. In classrooms where windows were more accessible to access and operate, teachers could maintain better air quality consistently.

5. **Real-time monitoring and adaptive strategies:** Studies like those by Ackley (2022) and NIWA (2022) emphasize the importance of real-time monitoring of classroom conditions to adjust ventilation practices dynamically. Integrating sensors and data analytics aids in providing continuous feedback, ensuring optimal classroom environments. The need for adaptive strategies and real-time feedback mechanisms was evident. Teachers could better manage ventilation when aware of current IAQ levels. This informed approach helped address variations in CO₂ levels and TC effectively.
6. **Regulatory and guideline alignment:** Standards and guidelines from bodies like ASHRAE, WHO, and local NZ guidelines underpin the best practices for maintaining acceptable IEQ in school settings. Studies often reference these standards to validate their findings and ensure recommendations are aligned with regulatory expectations. The application of these guidelines in our analysis highlighted the need for adherence to established ventilation rates and temperature ranges. The regulatory framework provided a structured approach to assessing and improving classroom IEQ.

In general, the literature supports the findings by corroborating that weather conditions, architectural characteristics, adaptive ventilation practices, and continuous monitoring are essential factors that influence IEQ in classrooms. Both our study and the existing literature recognise the critical impact of these factors on student health, comfort, and cognitive performance, highlighting the importance of maintaining a balanced and proactive approach to classroom environmental management.

6.4 General discussion for observation studies and sensors

The study results on window and door sensor monitoring in primary school classrooms reveal significant behavioural differences between teachers in using window openings to maintain IAQ. This discussion will compare the study findings with existing literature on classroom ventilation and its impact on IAQ and TC.

The literature supports the conclusion that frequent and strategic window opening is essential to maintain good IAQ in classrooms. Studies by Toyinbo (2023) and

Gohara et al. (2022) emphasize that children spend much of their time indoors, necessitating good IAQ to prevent health issues. This aligns with the findings that Teacher 1 prioritised keeping the windows open, resulting in better IAQ, particularly in high-occupancy seasons like winter.

ASHRAE standards, especially ASHRAE Standards 55 (ASHRAE, 2020) and 62.1 (ASHRAE, 2022a), elaborate on the conditions for TC and minimal ventilation requirements to ensure healthy indoor environments. These standards support the study's recommendation to optimise window openings to maintain specific environmental parameters, confirming that Teacher 1's approach aligns more closely with established TC&V guidelines.

The adaptive comfort model of de Dear and Brager (1998; 2013) suggests that buildings that rely on natural ventilation should be adjusted to varying conditions. This model supports the seasonal adjustments observed in the study's window-opening behaviours, reflecting how Teacher 1 adaptively responded to changing weather conditions.

Wargocki and Wyon (2006; 2017b) focused on the impact of IEQ on cognitive and academic performance, underlining the need for optimal ventilation rates and temperatures. This supports the study's observation that effective window opening by Teacher 1 could enhance air circulation, thus improving cognitive performance through better IAQ.

Studies by Nicol et al. (2012) and McIntosh (2011) further highlight the importance of adaptive strategies in maintaining classroom environments and managing CO₂ levels through ventilation, supporting the study's emphasis on window management for enhanced air quality. Bennett et al. (2019) support this by highlighting the role of cross-ventilation in managing CO₂ levels, mirroring the study findings on effective window opening practices of Teacher 1.

Mainka (2018) highlights that modernised school buildings with better insulation must balance airtightness with effective natural ventilation strategies, backing the study analysis that adaptive window opening is crucial, especially as Teacher 1's consistent airing practices suggest.

The literature on seasonal window opening behaviour, such as Fromme et al. (2008) and Zapata-Lancaster (2023), further reinforces the study's observations on the impact of external conditions on IAQ. They document the practice of reduced window opening during the colder months, leading to elevated indoor CO₂ levels, which was also noted with the teacher 2's inclination to keep windows closed in autumn.

Furthermore, the emphasis on ventilation during the SARS-CoV-2 pandemic, highlighted in studies by Gohara (2022), Alonso (2021), Kulo (2021), and BurrIDGE et al. (2023), draws attention to the importance of maintaining good air quality to minimise disease transmission. This context supports the study findings that more consistent window openings, as practised by Teacher 1, can significantly improve air quality and mitigate health risks.

In summary, the research literature supports the study results by demonstrating the critical role of adaptive and strategic window openings in maintaining IAQ and TC in educational settings. The constant opening of Teacher 1's window is supported by various studies and guidelines, showcasing its effectiveness in promoting a healthier and more comfortable learning environment. Conversely, Teacher 2's preference for closed windows highlights the importance of balancing environmental control with adequate ventilation to ensure optimal IEQ. The nuanced approach highlighted by this review of the literature validates the study's findings and reinforces the need for targeted ventilation strategies in classroom settings.

6.5 Conclusions

6.5.1 Teachers questionnaire

In this study, the demographic profile revealed that the majority of respondents were women (81%) and over 40 years of age (70%), indicating a significant presence of experienced and potentially experienced educators. Teachers aged 50-59 years had the highest average teaching experience at 23 years, while those aged 60 and older averaged 34 years of experience. In contrast, younger teachers under 30 years had the least experience, averaging 3.8 years. This distribution of age and experience suggests that the study findings may predominantly reflect the opinions

and preferences of more experienced female teachers, potentially influencing the results related to teaching and classroom conditions (TC&V preferences).

Regarding the user-friendliness of the mechanisms, more than half (59%) of the respondents found the window and door handles user-friendly. The highest satisfaction was reported among the 50-59 age group. This finding is supported by statistically significant median ratings, indicating a consensus on the ease of use of these mechanisms.

Regarding the window opening frequency, the responses were almost equally split, with 39% agreeing that they open windows regularly during class, while 36% disagreed. This mixed behaviour suggests no clear trend and highlights the influence of various age groups on window-opening habits.

Regarding classroom comfort, a significant majority (76%) of respondents agreed that open windows contribute to a comfortable classroom environment. This sentiment was particularly strong among younger teachers and those over 60 years old, indicating a shared preference for natural ventilation among these age groups.

Opinions on the challenges of opening windows during windy days varied, and no significant consensus emerged from the data. This variation indicates differing practices across age groups when managing classroom ventilation under windy conditions.

A substantial majority (64%) of the respondents agreed that the design of the windows and doors provided adequate ventilation. This view was most strongly supported by younger teachers, suggesting that newer or more modern designs might better align with their expectations or needs for adequate ventilation.

Most of the respondents (58%) noted the odour of the classroom as an issue, particularly after activities or weekends. Younger teachers more frequently identified odour as a problem, indicating a possible age-related difference in IAQ perception.

Regarding the impact of outside noise, just over half (53%) of the respondents reported that noise discouraged them from opening windows. There were variations in responses between different age groups, which highlighted various sensitivities or

coping strategies when managing external noise.

Finally, safety concerns associated with open windows were reported by only a small percentage (12%) of the respondents. However, there was a clear consensus among older teachers, particularly those over 50 years of age, who strongly disagreed that open windows posed a safety hazard.

Regarding the preference for inverter heat pumps over window opening, the opinions were notably divided among the respondents. Approximately 41% favoured the use of heat pumps, while 40% were against it. This nearly equal split highlights a lack of strong consensus, indicating that preferences for classroom heating methods vary and potentially influence various factors.

The inverter heat pump usage patterns differed significantly between seasons and age groups. The younger and older teachers demonstrated an increased usage of these heat pumps during summer and winter. In contrast, middle-aged teachers showed more variability in their usage patterns, suggesting that this group may have different preferences or needs about classroom climate control based on seasonal changes.

The study's regional distribution was an important aspect, which revealed an imbalanced dataset. A disproportionate number of schools from the North Island, particularly Auckland, were included in the sample. This skew raises potential concerns about representation bias, as the findings may not accurately reflect the experiences and preferences of teachers from other regions, such as the South Island.

The correlation analysis observed a significant positive correlation between the user-friendly window and door mechanisms and perceptions of adequate ventilation. This finding suggests that the ease of operation of these mechanisms plays a critical role in maintaining classroom comfort and air quality. When windows and doors are easier to open and close, teachers are more likely to use them effectively to regulate airflow and maintain a comfortable learning environment.

Regarding the impact of odours and noise, the analysis revealed that odour perception was correlated with the use of heat pumps. This suggests that heat pumps may play a role in maintaining air quality, possibly by reducing unpleasant

odours in classrooms. However, noise concerns did not significantly influence window opening behaviour, indicating that external noise levels were not a major deterrent for teachers when deciding whether to ventilate their classrooms by opening windows. This highlights the complexity of factors that teachers consider when managing classroom environments and the importance of mechanical and natural ventilation solutions.

The study highlights the importance of understanding demographic influences on classroom environment management, the need for customised design solutions, and the role of education and training in improving teaching conditions and results.

6.5.2 Observation and window opening behaviour

- Day 1 (**Figures** 6.16 and 6.17):
 - The front doors, louvres and casement windows were open despite the overcast sky; high RH (96%) at 09:00.
 - The louvre windows provided air leakage, keeping CO₂ levels below 1000 ppm.
- Day 3 (**Figure** 6.18):
 - Front doors open; louvres and casement windows are mostly closed despite the clear sky.
- Temperature: Fluctuated between 14 °C and 21 °C with diurnal variations.
- RH: The morning highs (up to 96%) decreased to 60-70% in the afternoon.
- Windspeeds: Generally low, enabling the windows to remain open.

Window operations (mainly upon arrival at 08:30, comprising 43% of adjustments) were influenced by internal conditions and noise, particularly in S1-2 during pool time. The windows remained open for usage unless closed due to specific disturbances (**Figure** 6.21). Variations in classroom window operations reflect individualised teacher preferences despite unified guidelines (**Table** 6.7).

Spearman correlations were applied to factors such as temperature, humidity, and CO₂ to analyse the environmental impact on window usage. Significant positive

correlations existed between the open and indoor window area ($\rho = 0.758, p < 0.018$) and outdoor temperatures ($\rho = 0.893, p = 0.001$). Negative, though insignificant, correlations were observed with RH ($\rho = -0.341, p = 0.370$) and CO₂ ($\rho = -0.613, p = 0.079$).

The study revealed that teacher-initiated window operations, primarily upon arrival, were influenced by internal and external environmental factors. The findings suggest:

A tailored approach to ventilation in schools might prove significantly more effective than a one-size-fits-all policy. Given the observed differences in window operation practices among different classrooms, it is evident that teachers' preferences and specific classroom conditions profoundly influence ventilation strategies. Schools should consider developing individualised ventilation plans that cater to the unique needs of each classroom. This approach ensures that optimal air quality and temperature control are maintained, thus enhancing the overall learning environment.

Environmental awareness training for teachers is crucial to successfully implement these individualised ventilation strategies. Enhanced training programs should educate teachers on the importance of responding to varying environmental conditions such as temperature, humidity, and air quality. Empowering teachers with knowledge of effective ventilation practices can lead to more informed decisions, ensuring a healthier indoor environment for students.

Considering automated ventilation systems in classrooms presents a promising solution to the inconsistencies observed in manual window operations. Automated systems that respond to environmental data in real time could ensure more reliable and efficient IAQ management. These systems can help maintain consistent and optimal conditions without relying solely on manual interventions, thus reducing the burden on teachers and improving overall air quality control.

The **impact of variable ventilation practices on IAQ, TC, and student performance** cannot be overlooked. Different window operation approaches can lead to significant differences in IAQ and TC between classrooms. These variations can affect students' health and comfort, consequently influencing their academic performance. Ensuring consistent and optimal ventilation practices is essential for maintaining a conducive

learning environment.

From an **energy efficiency point of view**, inconsistent window operations can result in fluctuating levels of energy consumption. Schools may benefit from implementing standardised ventilation approaches or integrating smart technologies that regulate air quality and temperature more effectively. These measures can help reduce energy waste and promote more sustainable building management practices.

Policy development should consider the findings of such studies, especially in the context of the post-COVID-19 guidelines. The insights from the variability in ventilation practices can inform more nuanced and effective school policies prioritising health and energy efficiency. Tailored policies that reflect the unique needs of individual classrooms while promoting optimal IAQ and TC are likely to be more successful.

The results suggest that individual teacher preferences rather than overarching guidelines primarily influence window adjustment practices, affecting ventilation consistency and IAQ. Statistical correlations underscore the significant role of environmental factors, such as temperature and humidity, in window operations.

6.5.3 Window and door sensors

This section presented the results of window and door sensor monitoring in primary school classrooms, focussing on airing behaviours and their impact on IAQ. The study highlights significant differences in window opening practices between two teachers in different terms, reflecting their strategies to balance TC and ventilation.

Key Findings

The key findings of this study reveal several important aspects of window and door sensor monitoring in primary school classrooms. Initially, the response rate was hampered by frequent power failures and data errors, which led to a narrow focus on selected classrooms. Specifically, eight sensors were installed in classrooms S1-1 and S1-3, and six sensors in S1-2, with data recordings logged every 5 seconds to ensure complete monitoring.

When validating the sensors, anomalies caused by battery depletion highlighted the need for regular maintenance. This issue was quickly addressed by replacing the batteries, restoring the validity of the study and allowing more reliable data collection.

A comparative analysis of teacher behaviour revealed significant differences in window-opening practices between two teachers over different periods. Teacher 1, in 2023, preferred keeping windows open more frequently, which contrasted with Teacher 2, in 2024, who tended to keep windows closed. Various factors influenced these behaviours, including personal preferences and possibly other external conditions.

Meteorological conditions also played a role in shaping window-opening practices. The study found a strong correlation between increased wind speed and increased window opening, indicating that the weather impacted the ventilation behaviours observed in classrooms. These findings highlight the importance of considering environmental conditions when evaluating and implementing strategies to maintain IAQ.

The data show that adaptive window management affects IAQ in educational settings. Teacher 1's consistent window-opening practices suit improving IAQ, reflecting a proactive approach to balancing ventilation and temperature control. Conversely, Teacher 2's tendency to keep windows closed correlates with less favourable IAQ, emphasising the need for a balanced approach.

In general, this study highlights the crucial role of window management in maintaining optimal IEQ in classrooms. It aligns with the larger literature advocating adaptive strategies, continuous monitoring, and adherence to regulatory standards to enhance learning environments. The insights reinforce the need for targeted ventilation strategies tailored to specific classroom contexts and environmental conditions.

6.6 Relationship between Aim 1 and Aim 2 results

The analysis of the relationships between the results of Aim 1 and Aim 2 reveals two interconnected, yet distinct, research focusses.

The study on TC&V highlights the considerable challenges of seasonal variability in maintaining optimal temperatures and managing RH levels in classrooms throughout NZ. By examining regions such as Christchurch, Dunedin, and Hawke's Bay, the research highlights the varying performances during distinct seasons, with significant disparities in maintaining IEQ. The study reveals the need for customised heating and cooling solutions, along with adaptive ventilation practices, to effectively address these seasonal challenges. Particularly notable is Dunedin's superior performance in maintaining CO₂ levels, offering valuable insights into regional practices that improve ventilation effectiveness.

The teacher questionnaire and observation study centres on teachers' experiences, behaviours, and perceptions of IAQ and TC within their classrooms. It highlights the significant impact of teacher preferences and environmental factors on window operation and ventilation practices. By examining regional imbalances and detailed demographic profiles, the study illustrates how user perceptions and behaviours influence the effectiveness of ventilation. Differences in age, experience, and regional representation offer a nuanced understanding of classroom conditions, demonstrating that effective IAQ management is deeply interconnected with individual educators' specific needs and practices.

6.6.1 Trends and deviations between the studies

Both studies consistently highlight the importance of **seasonal variability** in maintaining IEQ, emphasising that winter and summer pose the greatest challenges due to increased heating and cooling requirements. They both affirm the crucial role of **adaptive ventilation strategies**: the study on TC and CO₂ levels advocates for regional and season-specific solutions, while the teacher questionnaire and observation study highlight the need for individualised window operation practices based on real-time environmental conditions.

However, there are notable deviations in their scope and insights. The **TC and CO₂ levels** offers a comprehensive regional performance analysis, pinpointing specific needs and successes in cities such as Dunedin and Christchurch and suggesting broad-scale infrastructure improvements. In contrast, the **teacher questionnaire and observation study** provides micro-level insights, illustrating how teacher behaviours and sensory feedback directly influence daily classroom ventilation and air quality. It highlights individual differences and the vital role of teacher engagement and education in effectively maintaining IAQ.

6.6.2 Convergence and divergence:

Both studies converge in recognising the critical importance of **seasonal adaptations** and the need for strategies that consider external environmental conditions. They highlight the need **to improve classroom ventilation mechanisms** to achieve a balance between air quality and TC. However, they diverge in their focus and scope. The **teacher-focused study** places significant emphasis on the human element of classroom management, demonstrating how teachers' interactions with ventilation systems are influenced by personal preferences and practical challenges. In contrast, the study **of ventilation effectiveness** (TC and CO₂ levels) provides a broader systemic perspective, suggesting infrastructure updates and policy changes that can facilitate widespread improvements in IEQ.

6.6.3 Mutual implications

Combining insights from both studies can lead to a comprehensive approach to IEQ in classrooms. **Policy and infrastructure upgrades** should prioritise the findings of the TC and CO₂ study to guide local and national policy decisions, focussing on investments in modern HVAC systems with heat recovery units, shading devices and energy efficient insulation. Additionally, **teacher training and engagement** programs should be developed using insights from the teacher survey to emphasise effective ventilation practices and the critical role educators play in maintaining classroom IAQ. In addition, both studies advocate for **adaptive and real-time monitoring** by implementing smart controls and continuous monitoring systems to respond to environmental changes and manage IAQ efficiently and dynamically. This multifaceted approach ensures a holistic IEQ improvement, benefiting students

and staff.

Ultimately, these studies support each other's findings and emphasise a holistic approach combining infrastructure improvements with active engagement and education at the classroom level. This dual strategy is crucial for maintaining healthy and comfortable learning environments in diverse regions and varying seasonal challenges in primary schools in NZ.

Chapter 7

TC and CO₂: IMPLICATIONS FOR COGNITION

7.1 Introduction

Aim three targets the developmental stages of Year 5 and Year 6 students in primary schools in NZ (approximately ages 9-11), evaluating how classroom variables like TC&V affect cognitive abilities - specifically concentration, reasoning and memory, to inform interventions that optimise learning environments.

Given the challenges posed by COVID-19 and classroom constraints, this field-based study will benchmark cognitive function under typical learning conditions (Test 1), then explore the impact of marginal temperature increases in well-ventilated spaces (Test 2), and finally investigate the effects of closing doors and windows while using heaters (Test 3). This approach simulates real-world scenarios in which teachers adjust TC, which could affect CO₂ levels.

- Test 2 involved the brief activation of a heater before testing, without adjusting the windows.
- For Test 3, the windows were closed and the heater was activated approximately half an hour before, often during the students' lunch break, allowing the room to warm up before their return. The students then engaged in regular schoolwork for 10 to 15 minutes before beginning the cognitive tests with laptops and facemasks. Finally, the windows were fully opened to ventilate the room.
- Masks were incorporated into Test 3 study protocol for multiple reasons. First, during the 2023 pilot study, some students expressed concerns about occupying classrooms with closed windows. Therefore, masks were included

to mitigate potential student anxiety and ensure full participation. Second, masks served to control for placebo effects and olfactory cues. The awareness of CO₂ manipulation by participants could influence cognitive performance through anticipation or anxiety, regardless of actual CO₂ levels. Masking helped to blind participants to environmental manipulation, thus minimising this potential confounding. Third, elevated CO₂ levels often correlate with increased VOCs and other odours in poorly ventilated spaces. These factors can independently affect cognitive function, and masking helped mitigate their influence.

The study progresses from baseline conditions to subtle temperature changes and then to a situation where TC adjustments can inadvertently elevate CO₂ levels. By observing the **natural increase** in CO₂ under these conditions, the research aims to understand the interplay between TC, IAQ, and cognitive performance in educational settings.

This sequential examination of classroom conditions provides insight into factors influencing students' learning experiences while acknowledging practical constraints teachers face in NV classrooms. The methodology allows for a nuanced exploration of how environmental factors impact cognitive functioning in real-world educational environments.

7.2 Results of cognitive tests

7.2.1 Response rates

Table 7.1 details the numbers of participants for each cognitive evaluation under varying test conditions, following the exclusion of invalid responses.

TABLE 7.1: Participant Numbers by Date and Test Protocol, Adjusted for Accuracy

		Test 1				Total	Test 2				Total	Test 3				Total	
Date	Room	DT	SP	SS	OO		DT	SP	SS	OO		DT	SP	SS	OO		
19/3	S1-2	17	20	20	18	75						17	16	15	16	64	
22/3	S1-1	14	14	13	13	54											
	S1-3am	18	19	19	16	72											
	S1-3pm	19	19	19	18	75											
4/4	S1-1	15	14	13	15	57	14	14	15	13	56						
	S1-2						20	20	19	18	77						
8/4	S1-1	15	14	13	15	57						12	13	13	12	50	
	S1-3	15	16	16	13	60	17	17	17	15	66						
29/5	S1-3											16	18	18	15	67	
30/5	S1-2						20	18	17	16	73						
5/6	S1-2											15	19	18	15	67	
11/6	S1-2	13	13	12	11	49											
12/6	S1-1am						15	15	13	13	56						
	S1-1pm						12	13	12	12	49						
18/6	S1-2						15	14	14	14	57						
21/6	S1-1											13	12	12	11	48	
24/6	S1-2						17	17	15	16	65						
26/6	S1-1	13	13	13	9	48											
	S1-3						13	15	14	12	54						
School 1 - Classroom number							S1-1					S1-2		S1-3			
DT = Double Trouble							SP = Spatial Planning										
SS = Spatial Span							OO = Odd One Out										

The response rate of the participants shows a slight variation between tests (**Table 7.1**). The variation is due to unavoidable student departures during testing, including scheduled English for Speakers of Other Languages or Maths assessments and administrative summons. This potential fluctuation was anticipated and accepted before starting the study.

Table 7.2 details each classroom's cognitive test schedule and protocol during the extended 13-week collection period, superseding the initial 8-week plan.

TABLE 7.2: Test Dates, Room, Event Time and Corresponding Protocols

Date	Test 1	Test 2	Test 3
19/3	S1-2 AM		S1-2 PM
22/3	S1-1 AM S1-3 AMandPM		
4/4		S1-1 AM S1-2 AM	
8/4	S1-1 AM S1-3 PM	S1-3 AM	S1-1 AM
29/5			S1-3 PM
30/5		S1-2 AM	
5/6			S1-2 AM
11/6	S1-2 PM		
12/6		S1-1 AM & PM	
18/6		S1-2 PM	
21/6			S1-1 PM
24/6		S1-2 AM	
26/6	S1-1 PM	R3 PM	
DT - Double Trouble	SP - Spatial Planning	SS - Spatial Span	OO - Odd One Out

7.2.2 IEQ conditions

CO₂ data combines **steady-state measurements** from wall-mounted IEM units (Figure 4.4) and **instantaneous** readings from a portable Q-Trak 7575 (Figure 7.1) monitor during cognitive tests.

FIGURE 7.1: Position of QTrak in Classroom



This dual approach provides targeted measurements during assessments and continuous long-term monitoring (Aim 1), offering a comprehensive view of IEQ and its potential cognitive impact.

This allowed the PI to:

1. Correlate (Temp, RH and CO₂) conditions at the exact time of cognitive testing (using Q-Trak data).
2. Understand long-term indoor environmental conditions (using IEM data).
3. Cross-validate measurements between the two devices for increased reliability.
4. Capture a wider range of environmental parameters that might affect cognitive performance.

Table 7.3 presents the summary mean values and SDs for temperature, RH, and CO₂ levels observed under each test protocol. For results of each test, please refer to **Appendix H.1**.

TABLE 7.3: *Summary Mean [SD] of Environmental and Metabolic Parameters for Test Protocols*

Room	Test	Temp (°C)	RH (%)	CO ₂ (ppm)
S1-1	1	23.6 [2.8]	51 [13]	567 [107]
	2	23.8 [1.7]	49 [4]	864 [85]
	3	24.6 [1.6]	54 [4]	1148 [130]
S1-2	1	24.1 [0.7]	46 [3]	550 [42]
	2	25.0 [1.8]	51 [10]	765 [157]
	3	24.6 [2.7]	39 [1]	1134 [242]
S1-3	1	21.8 [0.7]	56 [2]	529 [46]
	2	21.4 [0.7]	54 [2]	685 [40]
	3	22.9 [0.2]	51 [1]	1476 [26]

To summarize the results of **Table 7.3**:

- Temperature (°C) generally increased from Test 1 to Test 3, with mean values ranging from 21.4 °C to 25.0 °C across all rooms.
- Relative Humidity (%) showed variable patterns, with no consistent trend across tests or rooms. The values ranged from 39% to 56%.
- CO₂ levels (ppm) increased consistently from Test 1 to Test 3 in all rooms:
 - Test 1: 529–567 ppm
 - Test 2: 685–864 ppm
 - Test 3: 1134–1476 ppm
- Room S1-3 exhibited the highest CO₂ increase in Test 3, reaching 1476 ppm.

This summary highlights the environmental changes across test protocols, particularly the significant increase in CO₂ levels from Test 1 to Test 3.

7.2.3 Testing for homogeneity of variance

A Levene's Test was conducted on the results of the cognitive tests. Although the classrooms are in the same school, factors such as teacher styles, class composition, or even physical classroom attributes could lead to differences in test outcome variability. Levene's test will help the PI know these potential differences and adjust

the analyses and interpretations accordingly.

The results of Levene's Test are presented in **Table 7.4**.

TABLE 7.4: *Levene's Test for Homogeneity of Variance Results by Classroom*

Room	Df	F value	<i>p</i> -value
S1-1	2	0.821	0.440
S1-2	2	5.122	0.006
S1-3	2	4.406	0.012

Table 7.4 presents a consolidated overview of the four cognitive tests combined for each classroom under test conditions. For detailed breakdowns of individual test results and analyses of specific conditions, refer to **the Appendix H.2**, which provides granular data for an in-depth examination.

S1-1 exhibits consistent score variability across test conditions, while S1-2 and S1-3 show significant differences, particularly pronounced in S1-2. This suggests that classroom-specific factors may influence the consistency of cognitive test performance under varying conditions.

7.2.4 Testing for normality

A detailed analysis breakdown is available in **Appendix H.3** for the reader's consideration. This section will contain only the summary.

The study examined the effects of different environmental conditions on cognitive performance in three classrooms (S1-1, S1-2, and S1-3) using four cognitive tests: Double Trouble (DT), Spatial Planning (SP), Spatial Span (SS), and Odd One Out (OOO). Conditions included Test 1 (teacher-managed environment with natural ventilation), Test 2 (marginally elevated warmth), and Test 3 (elevated CO₂ and temperature with face masks). The results varied between rooms and tests, but some consistent patterns emerged. The SS test showed significant effects across all conditions and rooms, suggesting that working memory and attention are susceptible to environmental changes. DT tests often showed significant effects in Test 1 and Test 2 conditions but not in Test 3. OOO test generally did not show significant effects in all conditions. Test 3 condition consistently impacted cognitive

performance most, with only SS showing significance in most cases. Room-specific variations were observed, particularly for SP, which showed strong effects in Test 1 conditions in S1-3 but not in S1-2. These findings highlight the complex interplay between environmental conditions and cognitive performance, emphasising the importance of considering room-specific and task-specific factors in such studies. The results also suggest that different cognitive tasks can be affected differently by environmental changes, with some tasks more resistant to variations in temperature and CO₂ levels than others.

The following section details the results of the ANOVA tests, providing a statistical comparison of cognitive performance under varied environmental conditions.

7.2.5 ANOVA tests

Within classroom ANOVA results

A **one-way** ANOVA (**Table 7.5**) was undertaken to determine if there were any statistically significant differences in cognitive performance among the three cohorts under the three different classroom environment conditions.

The complete analysis is available in **Appendix H.4.1**. The summary results for (**Table 7.5**) reveal varying performance patterns in three rooms (S1-1, S1-2, and S1-3) under different environmental conditions (T1, T2, and T3). The data show considerable variations in degrees of freedom and mean squares, indicating unequal sample sizes and differing variances between conditions and rooms. **In S1-1, the T2 condition (marginally elevated warmth) displayed the highest variance**, suggesting a greater variability in performance in this environment. **S1-2 exhibited the highest variance in the T1 condition**, while **S1-3 showed the greatest variance in the T2 condition**, similar to S1-1. These variations hint at the potential influences of environmental factors on the performance of the SS test.

TABLE 7.5: ANOVA Results: Impact of Classroom Environment on Student Cognitive Performance (Within Classroom)

Room	Cognitive Test	Condition	Df	SumSq	MeanSq
S1-1	Double Trouble	T1	41	11,623.33	283.50
S1-2	Double Trouble	T1	29	5,624.97	193.96
S1-3	Double Trouble	T1	51	8,584.98	168.33
S1-1	Double Trouble	T2	40	8,651.81	216.30
S1-2	Double Trouble	T2	71	11,836.00	166.70
S1-3	Double Trouble	T2	29	6,263.87	216.00
S1-1	Double Trouble	T3	24	4,548.16	189.51
S1-2	Double Trouble	T3	31	5,302.00	171.03
S1-3	Double Trouble	T3	15	3,049.00	203.27
S1-1	Spatial Planning	T1	40	4,413.81	110.35
S1-2	Spatial Planning	T1	32	2,834.55	88.58
S1-3	Spatial Planning	T1	53	2,561.33	48.33
S1-1	Spatial Planning	T2	41	4,972.79	121.29
S1-2	Spatial Planning	T2	68	5,387.07	79.22
S1-3	Spatial Planning	T2	31	1,087.72	35.09
S1-1	Spatial Planning	T3	24	2,462.64	102.61
S1-2	Spatial Planning	T3	34	1,577.14	46.39
S1-3	Spatial Planning	T3	17	919.78	54.11
S1-1	Spatial Span	T1	38	25.74	0.68
S1-2	Spatial Span	T1	31	52.22	1.68
S1-3	Spatial Span	T1	53	36.82	0.70
S1-1	Spatial Span	T2	39	42.40	1.09
S1-2	Spatial Span	T2	64	61.94	0.97
S1-3	Spatial Span	T2	29	29.87	1.03
S1-1	Spatial Span	T3	24	18.96	0.79
S1-2	Spatial Span	T3	32	31.52	0.99
S1-3	Spatial Span	T3	17	14.94	0.88
S1-1	Odd One Out	T1	36	825.89	22.94
S1-2	Odd One Out	T1	31	916.88	29.58
S1-3	Odd One Out	T1	45	737.74	16.39
S1-1	Odd One Out	T2	37	623.40	16.85
S1-2	Odd One Out	T2	63	1,205.44	19.13
S1-3	Odd One Out	T2	26	536.30	20.63
S1-1	Odd One Out	T3	22	528.44	24.02
S1-2	Odd One Out	T3	30	327.10	10.90
S1-3	Odd One Out	T3	14	129.73	9.27

Between classroom ANOVA results

A **between** ANOVA (Table 7.6) was carried out.

TABLE 7.6: ANOVA Results: Impact of Classroom Environment on Student Cognitive Performance (Between Classroom)

Condition	Cognitive Test	df	SUMsq	MEANsq	F value	Pr(>F)
T1	Double Trouble	2 (121)	2,813.00	1,406.60	6.59	0.002
T1	Spatial Planning	2 (125)	394.00	197.15	2.51	0.085
T1	Spatial Span	2 (122)	3.09	1.55	1.65	0.197
T1	Odd One Out	2 (112)	384.90	192.47	8.69	0.000
T2	Double Trouble	2 (140)	300.00	150.10	0.79	0.458
T2	Spatial Planning	2 (140)	235.00	117.52	1.44	0.241
T2	Spatial Span	2 (132)	1.68	0.84	0.82	0.441
T2	Odd One Out	2 (126)	5.30	2.63	0.14	0.869
T3	Double Trouble	2 (70)	2,679.00	1,339.60	7.27	0.001
T3	Spatial Planning	2 (75)	515.00	257.71	3.90	0.025
T3	Spatial Span	2 (73)	0.53	0.26	0.29	0.746
T3	Odd One Out	2 (66)	100.00	49.99	3.35	0.041

The complete analysis results are available in **Appendix H.4.2**. The summary results for (Table 7.6) reveal:

Test 1 (Normal conditions): Significant differences between rooms were observed for DT ($p=0.002$) and OOO ($p=0.000$) tests, suggesting that room conditions notably affect cognitive flexibility and visual reasoning. A weak relationship was found for SP ($p=0.085$), while no significant effect was observed for SS ($p=0.197$). This indicates that different cognitive processes are affected differently by classroom environmental conditions in normal circumstances.

Test 2 (Marginally elevated warmth): Under these conditions, no statistically significant differences were found between rooms for the four cognitive tests. This contrasts with the results from normal conditions, suggesting that slightly elevated temperatures might equalise performance across different rooms.

Test 3 (Elevated CO₂ and temperature): In this scenario, significant differences between rooms were observed for most tests, with varying degrees of impact. The DT ($p=0.001$) test showed the strongest effect, followed by moderate effects on OOO ($p=0.041$) and SP ($p=0.025$). No significant difference was found for SS ($p=0.746$). **These results suggest that elevated CO₂ and temperature may amplify the impact**

of room-specific factors on cognitive performance, particularly for tasks involving cognitive flexibility, visual reasoning, and planning.

Overall, these findings highlight the complex interplay between environmental conditions, room-specific factors, and different cognitive processes in educational settings. They highlight the importance of considering these variables when assessing and optimizing Classroom cognitive performance.

The **between-classroom** ANOVA was performed due to:

- **Comparing cohorts:** The study includes three distinct cohorts. A between-classroom ANOVA allowed for comparing the performance of these different groups on the cognitive tests.
- **Comparing environmental conditions:** The study involves three different classroom environment conditions. An ANOVA helped determine if there are significant differences in cognitive performance across these conditions.
- **Test type comparison:** With four different cognitive tests, ANOVA was used to compare performance across these different test types.
- **Time of day comparison:** Since tests are conducted twice between 09:00 and 14:30, ANOVA was used to compare performance at different times of the day.

Tukey's HSD posthoc test results

A Tukey's HSD was performed to identify which specific test conditions (Test 1, 2, or 3) differ significantly. The detailed analysis is available in **Appendix H.4.3**. This section summarises Tukey's HSD post-hoc test results for tasks with p -values less than 0.05.

T1 DT: Significant differences were found between S1-2 and S1-1, and between S1-3 and S1-1. S1-2 and S1-3 had significantly lower scores than S1-1, but there was no significant difference between S1-2 and S1-3.

T1 OOO: Only a significant difference was found between S1-3 and S1-2, with S1-3 having significantly higher scores. There were no significant differences between S1-2 and S1-1 or between S1-3 and S1-1, although S1-3 tended to have slightly higher

scores than S1-1.

T3 DT: A significant difference was found only between S1-2 and S1-1, with S1-2 having significantly lower scores. There were no significant differences between S1-3 and S1-1 or S1-3 and S1-2, although S1-3's performance was intermediate between the other two rooms.

T3 SS: A significant difference was found only between S1-2 and S1-1, with S1-2 having significantly lower scores. S1-2's performance was intermediate but not significantly different from S1-1 or S1-2.

T3 OOO: Similar to T1 OOO, a significant difference was found only between S1-3 and S1-2, with S1-3 having significantly higher scores. S1-1's performance was intermediate but not significantly different from S1-2 or S1-3.

In general, S1-1 tended to perform well in most tasks, particularly in the DT and SS tasks. S1-3 showed strong performance in the OOO tasks. S1-2 often had the lowest scores, particularly in comparison to S1-1. These results suggest that room conditions can significantly impact cognitive task performance, but the effects may vary depending on the task.

Results of the Kruskal-Wallis and Dunn's tests

Kruskal-Wallis tests were conducted to detect group differences, with detailed analysis in **Appendix ??**. This section summarizes the Kruskal-Wallis results and Dunn's tests, identifying specific differing groups (DT, SP and OOO).

Double Trouble

The complete Kruskal-Wallis analysis is available in **Appendix H.5.1**. Kruskal-Wallis test for S1-1 and S1-3 is not significant.

Table 7.7 details Dunn's test for DT for S1-2.

TABLE 7.7: Results of Dunn's Test with Bonferroni Adjustments for Multiple Comparisons (S1-2 DT)

Test result	Interpretation
<pre> Comparison of x by group (Bonferroni) Col Mean- Row Mean T1 T2 ----- ----- T2 -3.166954 0.0023* T3 -1.414179 1.547645 0.2360 0.1826 alpha = 0.05 Reject Ho if p <= alpha/2 [1] "Dunn's test results for Room: 6" \$chi2 [1] 10.41877 \$Z [1] -3.166954 -1.414180 1.547646 \$P [1] 0.0007702233 0.0786545885 0.0608538196 \$P.adjusted [1] 0.00231067 0.23596377 0.18256146 \$comparisons [1] "T1 - T2" "T1 - T3" "T2 - T3" </pre>	• A statistically significant difference between T1 and T2 ($p_{\text{adjusted}} = 0.002$). • No significant difference between T1 and T3 ($p_{\text{adjusted}} = 0.235$). • No significant difference between T2 and T3 ($p_{\text{adjusted}} = 0.182$). • The main conclusion is a statistically significant score difference between T1 and T2. In contrast, no significant differences were found between the other pairwise comparisons.

These results suggest that the marginally elevated temperature (T2) had a significant impact on student performance in the DT task compared to the normal condition (T1). However, the elevated CO₂ and the temperature condition (T3) did not show significant differences between T1 and T2.

Spatial Planning

The complete Kruskal-Wallis analysis is available in **Appendix H.5.1**. Kruskal-Wallis test for S1-1 is not significant.

Table 7.8 details Dunn's test for SP for S1-2.

TABLE 7.8: Results of Dunn's Test with Bonferroni Adjustments for Multiple Comparisons (S1-2 SP)

Test result		Interpretation
<pre> Comparison of x by group (Bonferroni) Col Mean- Row Mean T1 T2 ----- ----- T2 -3.216973 0.0019* T3 -0.713418 2.446852 0.7134 0.0216* alpha = 0.05 Reject Ho if p <= alpha/2 [1] "Dunn's test results for Room: 6" \$chi2 [1] 12.5026 \$Z [1] -3.2169735 -0.7134184 2.4468525 \$P [1] 0.0006477528 0.2377934581 0.0072054906 \$P.adjusted [1] 0.001943258 0.713380374 0.021616472 \$comparisons [1] "T1 - T2" "T1 - T3" "T2 - T3" </pre>		- Significant difference between T1 and T2 conditions ($p_{\text{adjusted}} = 0.025$). - No significant difference between T1 and T3 ($p_{\text{adjusted}} = 0.713$). - Significant difference between T2 and T3 ($p_{\text{adjusted}} = 0.021$).

Table 7.9 details Dunn's test for SP for S1-3.

TABLE 7.9: Results of Dunn's Test with Bonferroni Adjustments for Multiple Comparisons (S1-3 SP)

Test result		Interpretation
<pre> Comparison of x by group (Bonferroni) Col Mean- Row Mean T1 T2 ----- ----- T2 -2.931137 0.0051* T3 -2.185229 0.200793 0.0433 1.0000 alpha = 0.05 Reject Ho if p <= alpha/2 [1] "Dunn's test results for Room: 7" \$chi2 [1] 10.42988 \$Z [1] -2.931138 -2.185230 0.200793 \$P [1] 0.001688615 0.014436005 0.420430211 \$P.adjusted [1] 0.005065844 0.043308016 1.000000000 \$comparisons [1] "T1 - T2" "T1 - T3" "T2 - T3" </pre>		- Significant difference between T1 and T2 ($p_{\text{adjusted}} = 0.005$). - No significant difference between T1 and T3 ($p_{\text{adjusted}} = 0.043$). - No significant difference between T2 and T3 ($p_{\text{adjusted}} = 1.000$).

1. General interpretations for SP results

- T2 significantly alters the environment compared to T1.
- T3 does not significantly impact conditions compared to the T1.
- Comfortable and well-ventilated environments (T1) generally lead to better student performance.
- **Both T2 and T3 conditions can negatively affect performance due to discomfort or decreased cognitive function.**

The findings emphasize the importance of environmental controls in educational settings, particularly regarding temperature and air quality management, to optimize student comfort and performance. The results suggest that even subtle changes in environmental conditions can impact spatial planning abilities.

Odd One Out

The complete Kruskal-Wallis analysis is available in **Appendix H.5.1**. Kruskal-Wallis test for S1-1 and S1-3 is not significant.

Table 7.10 details Dunn's test for DT for S1-2.

TABLE 7.10: Results of Dunn's Test with Bonferroni Adjustments for Multiple Comparisons (S1-2 DT)

Test result	Interpretation
<pre> Comparison of x by group (Bonferroni) Col Mean- Row Mean T1 T2 ----- ----- T2 -2.663017 0.0116* T3 -0.928054 1.566035 0.5301 0.1760 alpha = 0.05 Reject Ho if p <= alpha/2 [1] "Dunn's test results for Room: 6" \$chi2 [1] 7.622403 \$z [1] -2.6630178 -0.9280543 1.5660359 \$p [1] 0.003872166 0.176689703 0.058670105 \$p.adjusted [1] 0.0116165 0.5300691 0.1760103 \$comparisons [1] "T1 - T2" "T1 - T3" "T2 - T3" </pre>	• A statistically significant difference between T1 and T2 ($p_{\text{adjusted}} = 0.011$). • No significant difference between T1 and T3 ($p_{\text{adjusted}} = 0.530$). • No significant difference between T2 and T3 ($p_{\text{adjusted}} = 0.176$). • The main conclusion is a statistically significant score difference between T1 and T2. In contrast, no significant differences were found between the other pairwise comparisons.

The condition T2 stands out significantly compared to T1, highlighting that even a moderate increase in warmth (unnoticed by the participants) can affect their performance. Elevated CO₂ and temperature (with mask use) do not create drastic changes.

In summary, Kruskal-Wallis and Dunn's test revealed intriguing insights into the environmental impact on students. The normal environment (T1) served as a solid base, providing a standard reference point for comparison. Interestingly, **the slightly elevated warmth condition (T2) resulted in the lowest mean rank, suggesting that even minor temperature increases can negatively affect comfort or performance. Most surprisingly, the condition with elevated CO₂ levels, higher temperature, and mandatory use of the mask (T3) yielded the highest mean rank. This unexpected outcome challenges conventional assumptions about environmental comfort. Students may adapt more effectively to clearly defined changes or structured environments, even when they appear more challenging on the surface.**

The study's findings **shed light on students' adaptability to different environmental conditions**. In particular, the students demonstrated a superior ability to adjust to clearly defined changes, such as those in condition T3, which involved elevated CO₂ levels, higher temperature, and mask-wearing. In contrast, they struggled more with unexpected thermal changes, as seen in condition T2 with slightly elevated warmth. **This suggests that individuals may be better equipped to cope when aware of and prepared for environmental modifications**. Furthermore, the surprisingly positive results in T3 could be attributed to psychological adaptation or the Hawthorne effect (Favero et al., 2021; McCambridge et al., 2014; Ofori et al., 2022), where students' awareness of being in a controlled, test-driven environment could have positively influenced their performance and perception of comfort.

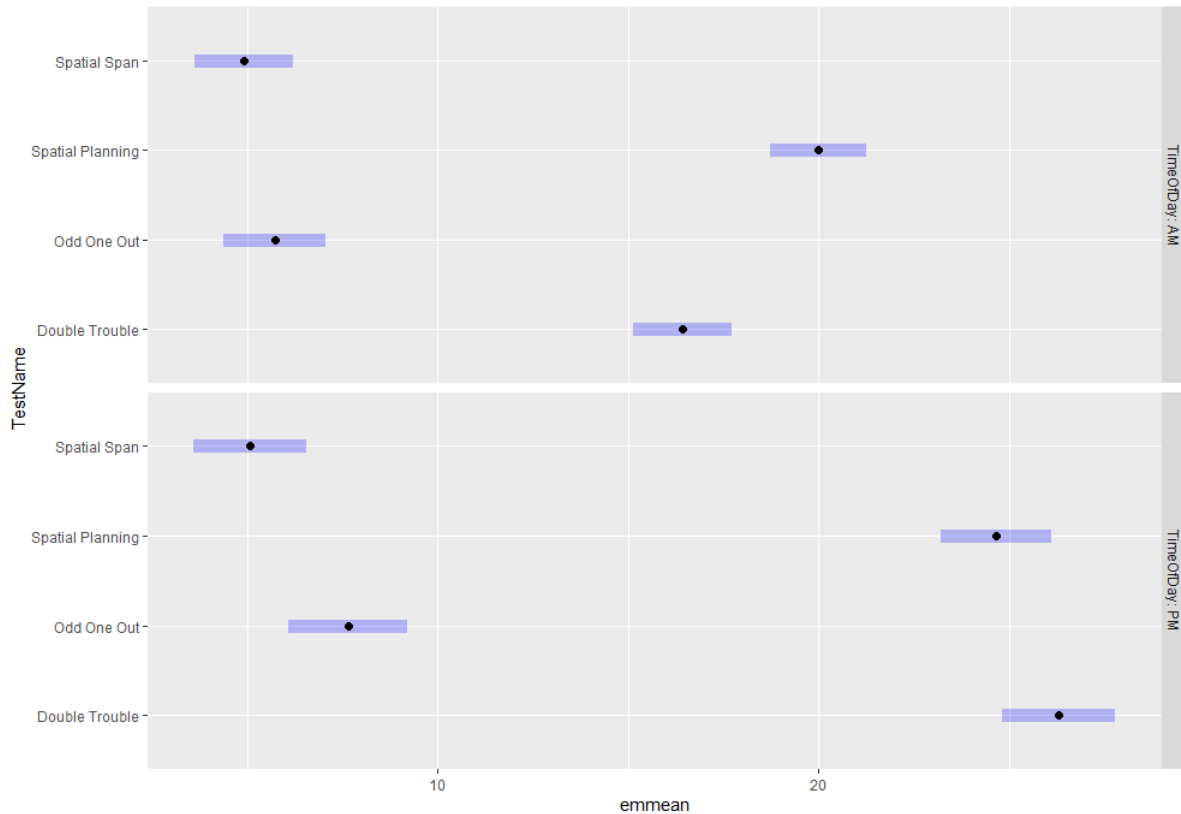
7.3 Impact of time on cognitive test results

Figure 7.2 displays the estimated marginal means (emmeans) for performance on four different cognitive tests administered at two different times of day: morning (AM) and afternoon (PM).

Each subplot in **Figure 7.2** compares the average performance of these tests at specified times of the day, providing insight into how cognitive performance can vary depending on the administration time.

- The x-axis represents the estimated marginal means (emmeans), which reflect the average performance scores on each test.
- Each bar represents the mean performance, and the small black points within the bars depict the central value (mean), while the bar itself shows a confidence interval around the mean.

FIGURE 7.2: Comparison of Cognitive Test Performance at Different Times of the Day (AM vs. PM)



The aim is to determine whether there are significant differences in cognitive test performance between the morning and afternoon sessions.

Comparison of test performance:

- **DT:** Performance seems higher in the PM than in the AM.
- **SP:** Performance is higher in the PM compared to the AM.
- **SS:** Performance appears consistent between AM and PM with similar emmean values.
- **OOO:** There is no significant difference between the AM and PM performances; the values are very close.

The analysis reveals a nuanced pattern in cognitive performance in different tasks. **There is a notable improvement in performance for DT and SP during PM sessions**

compared to AM sessions. In contrast, tasks such as SS and OOO show relatively consistent performance regardless of the time of day.

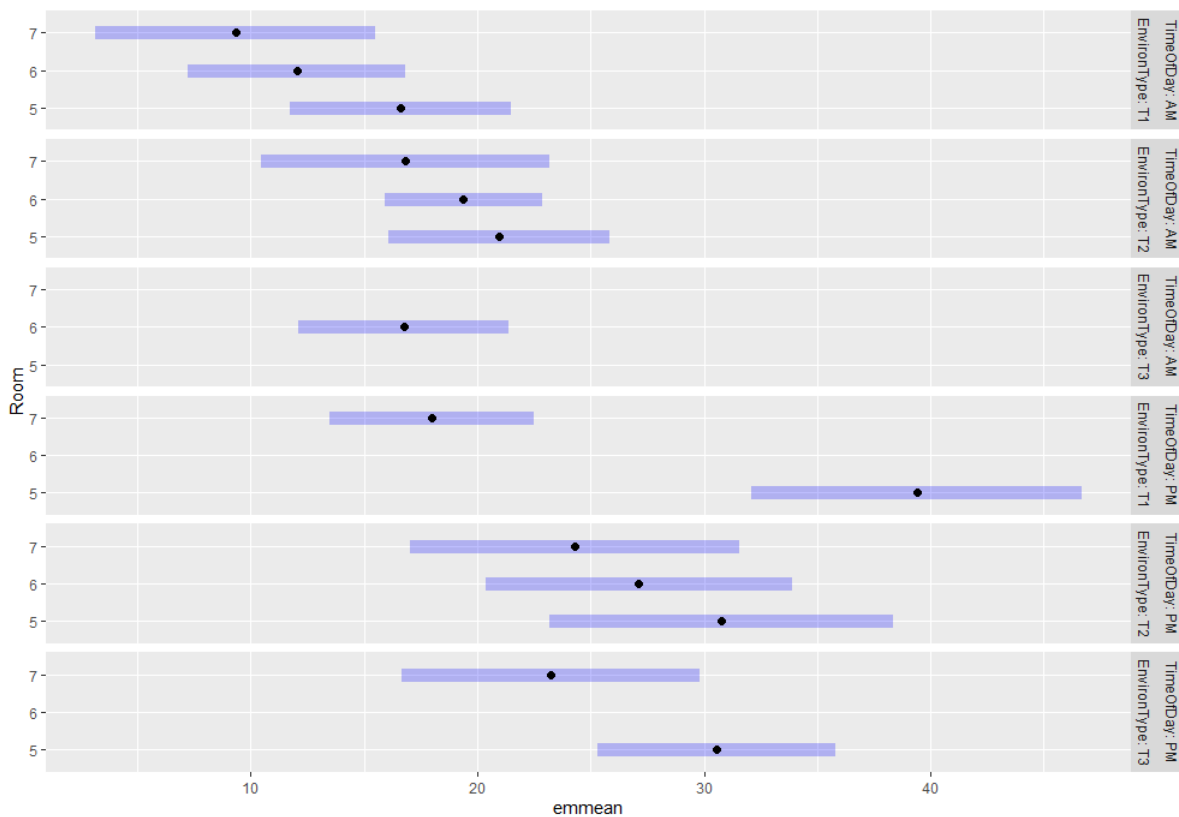
Given these task-specific trends, further detailed analysis will focus on DT and SP to better understand the factors influencing their improved afternoon performance. These tasks have been examined, with the complete analysis available in **Appendix H**. The following sections summarise the key findings and insights from this in-depth investigation.

Double trouble

The ANOVA results in **Appendix H.6.1** indicate significant main effects for Room, Test Condition, and Time of Day (all $p < 0.001$) on cognitive test performance. This suggests that these factors independently influence cognitive performance. However, the lack of significant interaction effects implies that the impact of these factors is consistent across different combinations of conditions.

Figure 7.3 shows the estimated marginal means for each test condition and cognitive test during AM and PM tests.

FIGURE 7.3: *Estimated Marginal Means (DT) of Room Measurements by Time of Day and Environment Type*



Pairwise comparisons and **Figure 7.3** reveal more nuanced findings in different test conditions and rooms. In T1, no significant differences were observed between the rooms in the AM. However, in the PM, S1-3 performed significantly worse than S1-1 (estimate = 7.601, $p = 0.0001$). S1-3 had the lowest temperature (21.81 °C) and higher relative humidity (56.22%), which may contribute to the observed performance differences.

In conditions of marginally elevated warmth (T2), no significant differences were found between rooms during the AM or PM sessions. Despite elevated temperatures and CO₂ levels compared to T1, the lack of significant differences suggests that these conditions did not significantly affect cognitive performance.

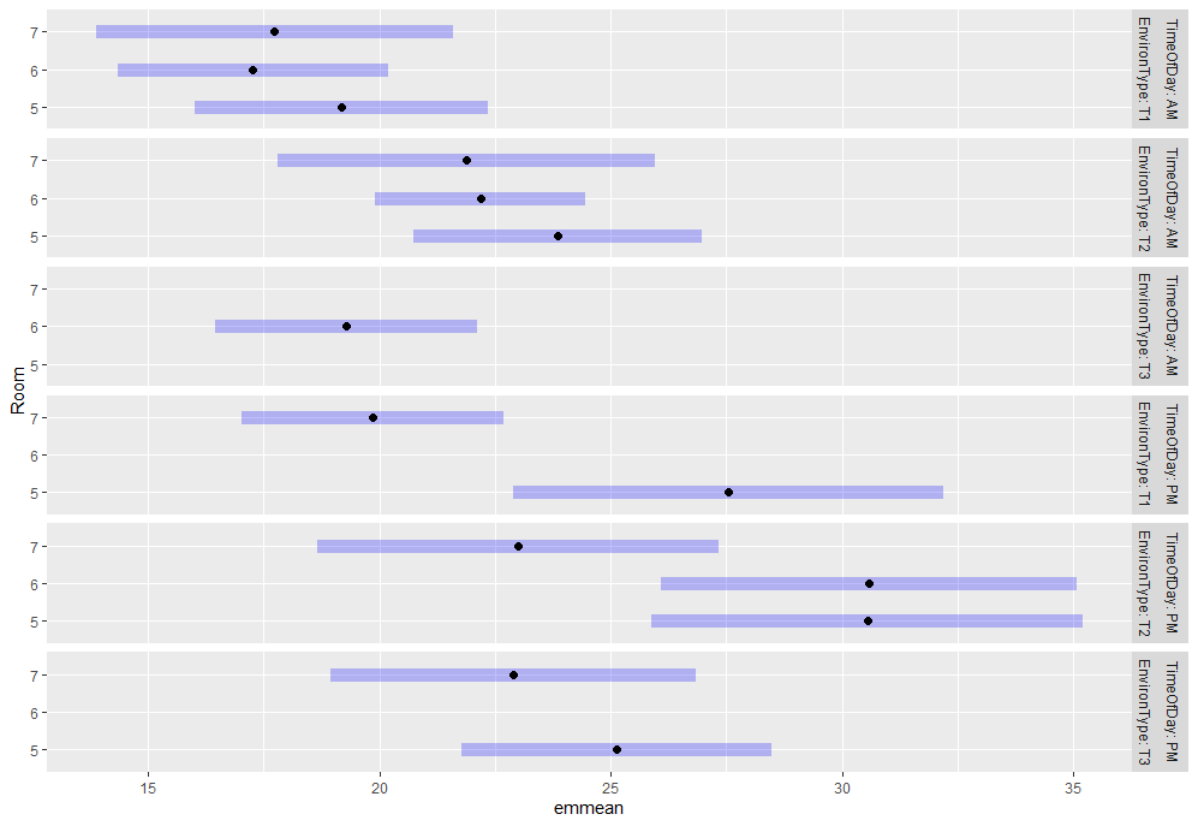
S1-3 had notably higher CO₂ levels (1476 ppm), potentially negatively affecting performance.

Overall, the results suggest that room conditions can influence cognitive performance, particularly in normal environmental settings. The impact of elevated temperature and CO₂ levels appears less pronounced in this dataset, though the incomplete data for T3 limits comprehensive conclusions. The significant differences observed in the PM session of T1 highlight the potential for effects of time of day on cognitive performance in room conditions.

Spatial Planning

Based on the provided information in **Appendix H.6.2** and **Figure 7.4**, the following summary has been created.

FIGURE 7.4: *Estimated Marginal Means (SP) of Room Measurements by Time of Day and Environment Type*



The study reveals significant impacts of classroom environmental conditions and time of day on primary school students' cognitive performance. The EnvironType factor emerged as the most influential, with T1 demonstrating better cognitive performance compared to conditions T2 and T3.

The time of day also played a crucial role, with afternoon sessions generally showing higher cognitive performance than morning sessions under various environmental conditions. This finding could have important implications for scheduling cognitively demanding tasks in primary schools.

Room-specific effects were observed, particularly in the T1 and T2 conditions, and S1-1 often outperformed S1-3 in the afternoon. However, these differences were less pronounced under the T3 condition, suggesting a potentially uniform effect of elevated CO₂ and temperature in different spaces.

The relationship between temperature changes and cognitive performance was complex and non-linear. Generally, slight temperature increases were associated with improved scores, with the greatest improvement observed in S1-1 for the transition from T1 to T2. Interestingly, S1-3 showed an inverse relationship for this transition, highlighting the complexity of this association.

CO₂ level was consistently associated with better scores, although their magnitude varied. The effect was more pronounced in T2 than in T3, indicating a possible threshold effect or interaction with other environmental factors.

Different rooms exhibited varying responses to environmental conditions, possibly due to differences in ventilation, heating efficiency, or structural factors. For example, S1-3 showed distinct spikes in estimated marginal means under the T3 condition, especially in the afternoon.

A consistent pattern of higher estimated marginal means was observed in the afternoon sessions in all environmental conditions, which could be attributed to the accumulation of heat or CO₂ during the day or possibly to the acclimatisation of the students.

These findings highlight the interaction between test conditions, time of day, and cognitive performance in primary school settings. They emphasise the importance of maintaining optimal classroom conditions, particularly TC&V, to support students' cognitive functions. The results also suggest potential benefits in scheduling cognitively demanding tasks in the afternoon, although this should be balanced with considerations of fatigue and attention span.

In conclusion, the results suggest that room-specific nuances and time of day impact cognitive test performance, with the most notable adverse effects observed in PM sessions under normal conditions. The marginal warmth condition seems to influence performance minimally, while elevated CO₂ and warmth require more precise data to conclude.

Other factors to consider in more detail for the future:

- Individuals in different rooms might have varying tolerance levels for changes in temperature and CO₂. Clothing, activity levels, and physiological differences can affect comfort and performance.
- The requirement of wearing face masks in T3 probably adds a layer of complexity to the interpretation of the data. Masks can increase perceived discomfort due to restricted airflow and increased CO₂ rebreathing (Eberhart et al., 2021; Smerdon, 2022).
- In T2, some participants became aware of the increased warmth, which might have influenced their performance or perception differently compared to T1 and T3. Psychological factors related to awareness and stress due to unexpected changes can also play a role (Favero et al., 2021; McCambridge et al., 2014; Ofori et al., 2022).

Concluding thoughts: The data from this field experiment provide valuable insight into how different environmental conditions affect a classroom setting. Variations observed between rooms, conditions, and times of day highlight the importance of optimising classroom environments for comfort and performance.

7.3.1 Temperature and Carbon dioxide effects based on time

Double Trouble

Exposure to suboptimal indoor environmental conditions, particularly relating to TC&V, can have significant impacts on cognitive performance. Understanding the combined effects of these factors is crucial to ensure a productive and healthy learning environment in schools.

Temperature effects between test conditions:

- R2(DT) shows the highest sensitivity to temperature changes, with large increase in scores per °C (9.68 and 8.28 points/ °C for T1(DT) to T2(DT) and T1(DT) to T3(DT), respectively).
- R1(DT) exhibits a much larger effect for T1(DT) to T3(DT) (7.19 points/ °C) compared to T1(DT) to T2(DT) (0.4 points/ °C).
- R3(DT) shows an inverse relationship for T1 (DT) to T2 (DT) (-13.08 points / °C), but a positive relationship for T1(DT) to T3(DT) (7.01 points/ °C).

The relationship between temperature changes and test scores varies between rooms and test conditions. In most cases, an increase in temperature is associated with better scores, but the magnitude of this effect differs significantly. S1-2(DT) consistently shows the highest sensitivity to temperature changes, with substantial score increases per degree Celsius for both the transitions T1 (DT) to T2 (DT) and T1 (DT) to T3 (DT). Interestingly, S1-1(DT) exhibits a much larger score improvement for the transition T1 (DT) to T3 (DT) compared to T1 (DT) to T2 (DT), suggesting that the effect of temperature may not be linear or could interact with other factors. S1-3(DT) presents a unique case, showing an inverse relationship between temperature and score for the transition T1(DT) to T2(DT), which aligns with the previous test results. This inconsistency between rooms highlights the complex nature of the temperature-performance relationship and suggests that other environmental or individual factors may influence the results.

CO₂ effects between test conditions:

- All rooms show increased scores with rising CO₂ levels, but the magnitude varies.

- For T1(DT) to T2(DT), R2(DT) has the highest increase in score per ppm CO₂ (0.0419 points/ppm), while R1(DT) has the lowest (0.0003 points/ppm).
- The transitions from T1 (DT) to T3 (DT) show more consistent scores increase per ppm CO₂ between rooms (0.0082 to 0.0119 points/ppm).
- The effect of CO₂ on scores appears to be non-linear, with potentially diminishing returns at higher concentrations.

The impact of CO₂ levels on test scores also shows variability between rooms and test conditions. All rooms show an increase in scores with increased CO₂ levels, but the magnitude of this effect differs. For the T1(DT) to T2(DT) transitions, Room 2(DT) exhibits the highest score increase per ppm of CO₂, while S1-1(DT) shows the lowest. However, for the transitions from T1 (DT) to T3 (DT), the increase in the score per ppm of CO₂ is more consistent between rooms, although generally lower than those observed in the transitions from T1 (DT) to T2 (DT) (except for S1-1). This pattern suggests that the relationship between CO₂ levels and performance may not be linear, with potentially diminishing returns at higher CO₂ concentrations. The variability in results between rooms and conditions underscores the complexity of the CO₂ performance relationship. Indicates that other factors, such as individual differences or adaptation to changing environments, can influence the results.

The results reveal notable differences in how rooms respond to changing test conditions. S1-(DT) consistently shows the highest sensitivity to temperature and CO₂ changes, particularly in the transition from T1 (DT) to T2 (DT). S1-1(DT), on the other hand, shows a more pronounced effect in the transition from T1 (DT) to T3, especially for temperature changes. S1-3(DT) exhibits unique patterns, including an inverse temperature-score relationship in the transition from T1(DT) to T2(DT). These differences suggest that room-specific factors, such as ventilation efficiency, room layout, or student characteristics, can interact with environmental changes to produce varied results. The consistent increase in scores from T1 (DT) to T3 (DT) in all rooms, despite higher CO₂ levels, indicates that the combination of elevated temperature and CO₂ could have complex, potentially beneficial effects on performance under certain conditions. However, these results also highlight the need for further investigation to understand the underlying mechanisms and potential long-term implications of these environmental changes on student performance.

Spatial Planning

Temperature changes were observed in all rooms during the study period. Generally, the temperatures increased from T1(SP) to T2(SP) and from T1(SP) to T3(SP) in most rooms. The only exception to this trend was S1-3(SP), which experienced a slight decrease in temperature from T1(SP) to T2(SP). Among all recorded changes, the most significant temperature increase was observed in S1-2 (SP), where the temperature increased by 0.93 ° C from T1 (SP) to T2 (SP). This substantial increase in S1-2 (SP) was the largest temperature change observed throughout the study.

The score changes were consistently positive throughout the study period in all rooms and conditions. Each room demonstrated an increase in scores, regardless of the time frame or condition evaluated. This uniform trend of improvement was observed in all the monitored spaces. In particular, the most substantial score increase was recorded in S1-2(SP), where a remarkable jump of 6.6 points occurred between T1(SP) and T2(SP). This significant improvement in S1-2(SP) was the most dramatic change among all the score increases observed during the study, highlighting a particularly strong performance enhancement in that specific room during that time interval.

The relationship between temperature and score changes showed significant variability in different rooms and conditions. The ratio of score change to temperature change fluctuated considerably, indicating a complex interplay between these factors. R1(SP) demonstrated the highest sensitivity to temperature variations from T1(SP) to T2(SP), with a remarkable 16.4 points increase/ °C. Interestingly, S1-3 (SP) showed an inverse relationship during the same period, with scores decreasing by 8.46 points/ °C increase. This contrast highlights the diverse responses to temperature changes in different spaces. However, when examining the relationship between T1 (SP) and T3 (SP), a more consistent pattern emerged in all rooms, with scores changing from 3.3 to 3.5 points/ °C. This suggests that over a longer period, the temperature-score relationship tended to stabilise and become more uniform across different environments.

7.4 Key findings from cognitive test results

1. **Environmental data collection:** The levels of temperature, relative humidity (RH) and CO₂ varied under different test conditions, as documented in **Table 7.3**, showing distinct environmental profiles for each classroom and test condition.
2. **Impact on cognitive performance:**
 - *Homogeneity of variance:* Significant variances in cognitive test scores were observed between different rooms, reflecting the influence of environmental conditions (as seen in **Table 7.4**).
 - *Normality testing:* The cognitive test scores showed patterns aligned with different thermal and CO₂ conditions, highlighting specific sensitivities in tasks such as SS and DT to environmental changes.
 - *Task-specific effects:* The findings revealed that certain cognitive tasks, particularly SS and DT, were more sensitive to elevated temperatures and CO₂ levels, suggesting that these parameters significantly affected working memory and cognitive flexibility.
 - *Time of day effects:* Performance in cognitive tasks varied with the time of day, with notable differences between morning and afternoon sessions, suggesting diurnal variations in cognitive abilities.
3. **ANOVA and Kruskal-Wallis tests:**
 - The results of the ANOVA (within and between classrooms) showed statistically significant differences in cognitive performance based on environmental conditions. The Kruskal-Wallis test further supported these findings, highlighting significant differences in DT and SP tasks under different thermal and CO₂ conditions.
 - The Tukey HSD post hoc test provided a detailed breakdown of pairwise comparisons, demonstrating significant performance differences between different rooms and test conditions, such as those in DT and OOO tasks.
4. **Adaptive responses and psychological factors:** The study found that the students exhibited better adaptability to clearly defined environmental changes, such as those in the CO₂-masked condition, than unexpected temperature changes, revealing psychological adaptation and potential Hawthorne effects.

CO₂ levels showed a consistent upward trend in all rooms, progressively increasing from T1 to T2 and then to T3. This uniform increase in CO₂ concentrations was observed in all monitored spaces, indicating a cumulative effect of changing environmental conditions on air quality. In contrast, RH exhibited more diverse and complex changes. The variations in RH were not uniform, showing different patterns in different rooms and conditions. This variability in RH suggests that humidity levels were influenced by a combination of factors, potentially including the specific characteristics of each room, the environmental manipulations implemented, and possibly other uncontrolled variables. These observations highlight the multifaceted nature of indoor environmental dynamics and underscore the importance of considering multiple parameters when assessing environmental conditions in such studies.

The significant influence of the **Room** suggests that studying in different classrooms notably impacts cognitive performance. Investigating the specific characteristics of each room that could contribute to this variation might be beneficial. This could include factors such as lighting, noise levels, and classroom layout. The significant effect of **Test conditions** indicates that environmental conditions in the classroom alter cognitive performance. Hence, maintaining optimal TC&V levels is crucial to enhance student performance. Since the **TimeOfDay** is highly significant, cognitive performance appears to be better at different times of the day. This could have implications for scheduling tests or important cognitive tasks during optimal times of the day for students. Although the interactions were insignificant, subtle interactions between the time of day and room or test condition can still exist and might require further detailed analysis.

7.5 Cognitive test results discussion

The review of academic research focusses on several areas, including IEQ, classroom ventilation, cognitive performance, and adaptive strategies.

The interaction between environmental conditions and cognitive performance in educational settings is a multifaceted topic that has been extensively studied in various contexts. Research findings indicate that even minor deviations in IAQ and

TC can significantly affect students' cognitive abilities and academic performance.

Test 1 results (Normal conditions) suggest that the conditions of the room significantly affect cognitive flexibility and visual reasoning, echoing the findings of Wargocki and Wyon (2007a) about the impact of TC on cognitive tasks.

Test 2 results (Marginally elevated warmth) highlight no significant differences between rooms, indicating that slightly elevated temperatures might level performance variances, contradicting some studies, but also aligning with others that suggest moderate warmth is less disruptive compared to extreme conditions (Sadrizadeh et al., 2022).

Test 3 results (Elevated CO₂ and temperature) reaffirm the negative impact of high CO₂ levels and temperature on cognitive performance, particularly on tasks that require cognitive flexibility and planning, as demonstrated by previous studies on the adverse effects of poor IAQ (Fromme et al., 2008; Y. Zhang et al., 2016).

Elevated CO₂ levels and reduced cognitive performance

According to the "Between" classroom ANOVA results of Test 3, significant differences were observed in the DT ($p=0.001$), OOO ($p=0.041$), and SP ($p=0.025$) tests under elevated CO₂ and temperature conditions. These findings support the existing literature, which indicates that high CO₂ levels negatively impact cognitive flexibility, visual reasoning, and planning abilities. Satish et al. (2012) found that increased CO₂ concentrations commonly found indoors led to significant decrements in decision-making performance. Similarly, Allen et al. (2017) reported a dramatic 50% reduction in cognitive function scores when CO₂ levels increased from 550 ppm to 1400 ppm, highlighting the severe effect of moderate CO₂ increases. Coley et al. (2007) also observed a correlation between higher CO₂ levels and decreased student attention and cognitive function. Furthermore, Wargocki and Wyon (2007a) and Bakó-Biró et al. (2012) documented that improved ventilation rates improved cognitive performance, highlighting the importance of adequate ventilation to support cognitive function.

The alignment is clear: elevated CO₂ levels had a pronounced negative impact on various cognitive tasks, which is well supported by previous studies. For example,

Satish et al. (2012) and Allen et al. (2017) noted significant cognitive performance decrements at higher CO₂ levels, which is mirrored in this study findings that elevated CO₂ and temperature conditions amplified impacts on cognitive tasks that require cognitive flexibility and visual reasoning.

Marginally elevated temperatures and ventilation

Within the classroom, the ANOVA results revealed that condition T2 (marginally elevated temperature) exhibited the highest variance in performance for S1-1 and S1-3, indicating that even slight temperature changes can affect variability in cognitive performance. However, the results of the classroom ANOVA Between (Test 2) did not show statistically significant differences for cognitive tests between rooms under marginally elevated temperature conditions, suggesting that minor increases in temperature could not significantly disrupt cognitive performance. These findings are supported by Wargocki and Wyon (2007b), who found that slight temperature reductions significantly improved cognitive performance, suggesting an optimal TC range for maintaining cognitive effectiveness. Bakó-Biró et al. (2012) also highlighted the benefits of maintaining good ventilation for cognitive performance, emphasising that even slight improvements can enhance cognitive function.

The findings of this study are mostly in agreement with the literature. Although Wargocki and Wyon (2007a) suggest that slight temperature changes can improve performance if they lead to better TC, the current study indicates that marginally elevated warmth might not significantly affect performance, although it increases variability. This nuanced result implies that context and individual sensitivity may vary the TC margins.

Improved ventilation and cognitive performance

Between the results of the classroom ANOVA (test 1, normal conditions) showed significant differences between the rooms for DT ($p=0.002$) and OOO ($p=0.000$), indicating that well-ventilated environments contributed to better performance in cognitive flexibility and visual reasoning tasks. General interpretations of the SP results suggest that comfortable and well-ventilated environments (T1) generally lead to better student performance. These study findings are supported by Wargocki and Wyon (2007a) and Bakó-Biró et al. (2007), which documented that improving ventilation rates led to better cognitive performance, highlighting that

maintaining a good IAQ is crucial for cognitive tasks. Furthermore, Allen et al. (2017) established that lower CO₂ levels, indicative of better ventilation, were correlated with significantly higher cognitive function scores.

The findings of the study are perfectly aligned with the existing literature that highlights the importance of good ventilation. Studies by Wargocki and Wyon (2007a) and Bakó-Biró et al. (2012) confirm that higher ventilation rates correlate with improved cognitive task performance, which is reflected in study observations under normal conditions (T1).

As discussed by de Dear and Brager (1998), the adaptive comfort model suggests that occupants can adapt to various temperatures, particularly in NV environments. This concept aligns with the findings that the students performed better under more predictable and manageable environmental changes, such as elevated CO₂ levels and mask-wearing, instead of sudden, marginally elevated warmth. The research by Nicol et al. (2012) further supports the relevance of adaptive TC models in classrooms, advocating for environments that allow occupants to control their microclimate through natural ventilation methods. These studies highlight the importance of providing adaptable and controllable indoor environments to enhance comfort and performance in educational settings.

The findings emphasise the importance of consistently monitoring and managing classroom thermal conditions and align well with recommendations from the US Green Building Council and BRE guidelines (2023). These advocate for holistic approaches to maintaining IEQ that consider multiple parameters such as ventilation, lighting, and thermals. The broader application of these findings to workplace settings is reflected in studies by Fisk (2000) and Mendell and Heath (2005), who demonstrated that improved IEQ enhances productivity and cognitive function in office environments, paralleling the educational context.

Unexpected findings

Despite well-established expectations, the study also revealed some surprising results, particularly under the T3 condition (elevated CO₂ levels, higher temperature, and mandatory mask-wearing). Kruskal-Wallis and Dunn's tests showed that the T3 condition yielded the highest mean rank, suggesting that students might adapt better

to clearly defined, structured changes rather than unexpected thermal increases. This result is supported by the concepts of psychological adaptation and the Hawthorne effect, which describe the phenomenon in which awareness of being in a test-driven environment or under observation can lead to improved performance, possibly due to increased motivation or effort (Favero et al., 2021; McCambridge et al., 2014; Ofori et al., 2022).

This finding challenges conventional assumptions, but is supported by psychological theories, such as the Hawthorne effect, which posits that individuals may perform better when they know they are being observed or when environmental changes are well defined and structured.

In conclusion, the study's findings align well with the established body of literature in several key aspects. Elevated CO₂ levels were consistently found to negatively affect cognitive performance, aligning with studies by Satish et al. (2012), Allen et al. (2017), and Coley et al. (2007). Similarly, the benefits of improved ventilation on cognitive performance are well supported by Wargocki and Wyon (2007a) and Bakó-Biró et al. (2012).

Marginally elevated warmth did not significantly alter performance, but did increase variability, suggesting that TC has a complex and context-dependent impact on cognitive function. This is partially supported by studies recommending optimal thermal conditions for cognitive performance.

Finally, the study uncovered unexpected findings regarding students' adaptability to structured changes in environmental conditions, supported by theories of psychological adaptation and the Hawthorne effect. These results highlight the nuanced relationship between environmental factors and cognitive performance, suggesting that students may better adapt to well-defined changes and stressing the importance of context and perception in environmental psychology.

The literature review validates many of the study's findings on the impact of environmental conditions on cognitive performance. Specifically, the results align well with established research on the adverse effects of elevated CO₂ levels and the benefits of improved ventilation. In addition, the study provides intriguing insights into how students adapt differently to marginally elevated warmth

versus more pronounced environmental changes, suggesting a nuanced interaction between comfort, awareness, and cognitive adaptation.

7.6 Impact of time on cognitive test results discussion

The ANOVA results (**Appendix H.6.1**) indicated significant main effects for Room, Test Condition, and Time of Day (all $p < 0.001$). This suggests that these factors independently influence cognitive test performance. The nuances revealed by pairwise comparisons and **Figure 7.3**—such as significant performance drops in the PM for room S1-3 under T1—underscored the role of environmental factors in cognitive performance. For example, S1-3 had the lowest temperature (21.81 °C) and the highest relative humidity (56.22%) between rooms, potentially contributing to the observed performance differences.

In marginally elevated heat (T2) conditions, the absence of significant differences in performance between AM and PM sessions confirms the complex interaction between cognitive function and environmental parameters. Although S1-3 still showed higher CO₂ levels (1476 ppm), these did not significantly affect cognitive performance, suggesting that there may be a threshold beyond which CO₂ impacts are more pronounced.

These results align with the findings of Satish et al. (2012) and Allen et al. (2017), who reported significant decrements in cognitive performance at higher CO₂ concentrations. Similarly, Coley et al. (2007) observed decreased attention levels in students exposed to higher CO₂ concentrations. Wargocki and Wyon (2007a) and Bakó-Biró et al. (2012) further support this by documenting improvements in cognitive performance with increased ventilation rates, highlighting the importance of maintaining a good IAQ.

The results from the SP study reveal significant impacts of classroom environmental conditions and the time of day on students' cognitive performance, with "test conditions" emerging as the most influential factor. Specifically, cognitive performance was generally higher in the afternoon sessions compared to the morning sessions under various environmental conditions. This finding underscores the

importance of considering the time of day when scheduling cognitively demanding tasks in primary schools.

- **Temperature and CO₂ impacts:** The relationship between temperature changes and cognitive performance was complex and non-linear. Although slight temperature increases were sometimes correlated with improved scores, such as the transition from T1 to T2 in S1-1, other instances showed inverse relationships, particularly in S1-3. Higher CO₂ levels were consistently linked to improved scores, albeit with varying magnitudes. These observations align with studies by Wargocki and Wyon (2007b) and Bakó-Biró et al. (2012), which highlight the beneficial effects of lower CO₂ levels and better ventilation on cognitive functions.
- **Room-specific effects:** The study noted that different rooms responded variably to environmental conditions due to ventilation, heating efficiency, or structural characteristics. For example, S1-3 showed distinct performance patterns under the T3 condition, particularly in the afternoon. This suggests a need for room-specific strategies when managing classroom environments.
- **Time of day:** A consistent pattern of higher cognitive performance was observed in the afternoon, which could be attributed to the accumulation of heat or CO₂ over the day and the acclimatisation of the students. However, this must be balanced against potential fatigue and decreased attention spans, which are well documented in the literature.

The results of DT show increases in temperature generally improved scores, especially in S1-2. However, S1-1 showed a more significant effect for the transitions from T1 to T3, suggesting a complex interaction between environmental factors. The pattern of CO₂ influence was similar, with S1-2 exhibiting the highest sensitivity. This concurs with findings from studies like Satish et al. (2012) and Allen et al. (2017), which reported substantial cognitive performance declines with higher CO₂ levels. These results highlight the importance of optimising classroom environments for cognitive performance, highlighting the nuanced interaction between temperature, CO₂, and performance. For example, maintaining temperatures in the recommended range (20-22 °C) and CO₂ below 1000 ppm (Chatzidiakou et al. (Chatzidiakou et al., 2015)) can significantly improve cognitive outcomes.

In conclusion, a broad body of literature supports the study's findings. The significant influences of room conditions, test conditions, and time of day on cognitive performance highlight the need to maintain optimal IEQ in classrooms. Studies have shown that high CO₂ levels and poor ventilation negatively impact cognitive flexibility, attention, and visual reasoning, as noted by Satish et al. (2017), Allen et al. (2017), and Coley et al. (2007). Wargocki and Wyon (2019) and Bakó-Biró et al. (2012) have shown that better ventilation improves cognitive performance, particularly in well-ventilated environments where CO₂ levels are kept low.

The observed improvements in performance during afternoon sessions may reflect circadian rhythms and the benefits of acclimatisation to classroom conditions throughout the day. However, potential fatigue must be managed, requiring a balance in scheduling cognitively demanding tasks. The findings also suggest the importance of customised room-specific interventions and the need for detailed environmental control to enhance educational outcomes. Future research should investigate these nuances to better understand and optimise learning environments in primary schools.

The insights gained from this study have broad applications beyond the immediate context of educational environments. These findings may be valuable for optimising workplace settings where environmental conditions significantly impact employee comfort and productivity. In addition, the results can inform the formulation of policies, guiding the development of evidence-based regulations for IEQ in schools, offices, and other public spaces. This is particularly relevant in evolving health protocols and pandemic scenarios. Furthermore, the results of the study can be integrated into smart building technologies, enhancing the capabilities of automated HVAC systems and environmental sensors. Using these technologies, it becomes possible to maintain optimal conditions based on real-time data, creating more adaptive and responsive indoor environments. Ultimately, these broader applications can improve well-being, productivity, and energy efficiency in various sectors.

7.7 Reflection on methodological strengths and limitations

The study used several strengths in methodology. Conducted in real-world classroom settings, it used authentic cognitive tasks on individual laptops, allowing for a natural assessment of environmental impacts on cognitive performance. The familiar and comfortable surroundings, combined with gamified cognitive tests, enhanced student engagement and enjoyment; some students even continued with the tutorials voluntarily in later study stages.

The ability of students to choose their seats based on personal comfort further maintained the natural setting and offered information on how individual seating preferences could influence cognitive performance. Including various environmental conditions (managed by the teacher, marginally elevated heat and elevated CO₂ and temperature) added depth to the findings by examining various factors influencing cognitive abilities.

Data analysis leveraged visualisation tools in the R programming environment, facilitating clear interpretation and communication of the interaction effects between cognitive performance and environmental variables. By treating each classroom as a unique cohort and focussing on cohort-level analysis, the study effectively captured the overall impact of environmental conditions without being encumbered by individual demographic data.

However, the methodology has limitations. The absence of self-reported data on student awareness of environmental conditions could introduce inaccuracies. Furthermore, not analysing demographic data means that potential differences in cognitive performance based on gender, socioeconomic status, or learning disabilities were not considered.

The reliance on individual laptops for cognitive tasks, while a strength in terms of engagement, may limit the generalisability of the findings to other contexts or age groups. Furthermore, focussing exclusively on Year 5 and Year 6 students in primary schools in NZ could restrict the broader applicability of the results to different educational settings or age groups.

In general, the methodology used in this study offers valuable insights into the impact of environmental variables on cognitive performance in real classroom settings. However, potential biases and limitations should be considered, and caution should be exercised when generalising the results.

7.8 Conclusions

This chapter has explored the intricate relationship between TC and CO₂ levels on cognitive performance in Year 5 and Year 6 students within NZ primary schools. The study's findings underscore the crucial impact of classroom environmental conditions on various cognitive abilities, such as concentration, reasoning, and memory. Here is a concise summary of key conclusions drawn from the research.

7.8.1 Summary of cognitive findings

1. Environmental data collection:

- Temperature: A consistent increase was observed from Test 1 (baseline) to Test 3 (elevated conditions), with mean values ranging from 21.4 °C to 25.0 °C.
- Relative humidity: Showed varied patterns with values ranging from 39% to 56%.
- CO₂ levels: The percentage increased consistently from Test 1 (529-567 ppm) to Test 3 (1134-1476 ppm).

2. Impact on cognitive performance:

- Homogeneity of variance: Significant variances in cognitive test scores were influenced by environmental conditions, particularly noticeable in SS and DT tasks.
- Task-specific effects: Elevated temperatures and CO₂ levels affected working memory and cognitive flexibility.
- Time of day effects: Cognitive performance varied, with notable differences between morning and afternoon sessions across all test conditions.

3. ANOVA and Kruskal-Wallis tests:

- ANOVA results: Demonstrated statistically significant differences in cognitive performance based on environmental conditions.
- Tukey's HSD posthoc tests: Highlighted significant performance differences under different room and test conditions.

4. Adaptive responses and psychological factors:

- Students adapted better to structured environmental changes, such as elevated CO₂ levels and mask-wearing, compared to sudden, marginally elevated warmth. This suggests psychological adaptation and potential Hawthorne effects.

7.8.2 Key research conclusions

Elevated CO₂ levels negatively impact various cognitive tasks, highlighting the critical need to maintain low CO₂ concentrations, ideally around 1000 ppm, to optimise cognitive performance. High CO₂ levels can impair attention, decision-making, and overall cognitive functioning, directly affecting student learning and academic success. Therefore, effective ventilation strategies and monitoring systems must ensure that classroom air quality remains within optimal limits.

Marginally elevated temperatures appeared to disrupt cognitive performance minimally; however, they did increase variability in the results. This finding suggests a more complex relationship between TC and cognitive function than previously understood. Although slight temperature increases might not drastically affect performance, they can lead to inconsistent outcomes, indicating that maintaining a stable and comfortable temperature range is important to maintain optimal cognitive performance.

As demonstrated in the conditions of Test 1, improved ventilation significantly improved cognitive flexibility and visual reasoning tasks. This finding highlights the importance of good indoor air quality (IAQ) in educational settings. Adequate ventilation helps reduce CO₂ levels and maintain TC, both vital to creating an environment conducive to learning and cognitive activities.

Performance variation in different rooms was another critical observation that emphasised the influence of specific characteristics of the classroom, such as ventilation efficiency, room layout, and structural properties. When managing classroom environments, these room-specific factors must be carefully considered to ensure that all students benefit from optimal learning conditions. The unique attributes of each classroom can significantly impact how environmental changes affect cognitive performance.

Finally, the time of day significantly influenced cognitive performance, and the students performed better in the afternoon. This suggests that more demanding cognitive tasks might be better scheduled later in the day to take advantage of higher performance levels. However, this must be balanced with the potential for increased fatigue in the afternoon, which requires a thoughtful approach to scheduling to maximise cognitive efficiency without overburdening students.

7.8.3 Concluding remarks

This study contributes to the understanding of how different environmental factors, particularly TC and CO₂ levels, influence cognitive performance in primary school students. The findings highlight the need for well-ventilated, thermally comfortable classrooms to optimise learning conditions. Practical applications include implementing stricter environmental monitoring and control systems in schools, which can have far-reaching benefits not only in educational settings but also in various other domains where cognitive performance is crucial.

In conclusion, this research provides a foundation for further exploration of the interplay between environmental conditions and cognitive performance. The insights gained here pave the way for the implementation of evidence-based strategies to promote healthier, more productive indoor school environments and beyond. We can enhance students' learning experiences and overall well-being by continuing to investigate and address these critical factors.

Chapter 8

CONCLUSIONS, "SO WHAT", and FUTURE STUDIES

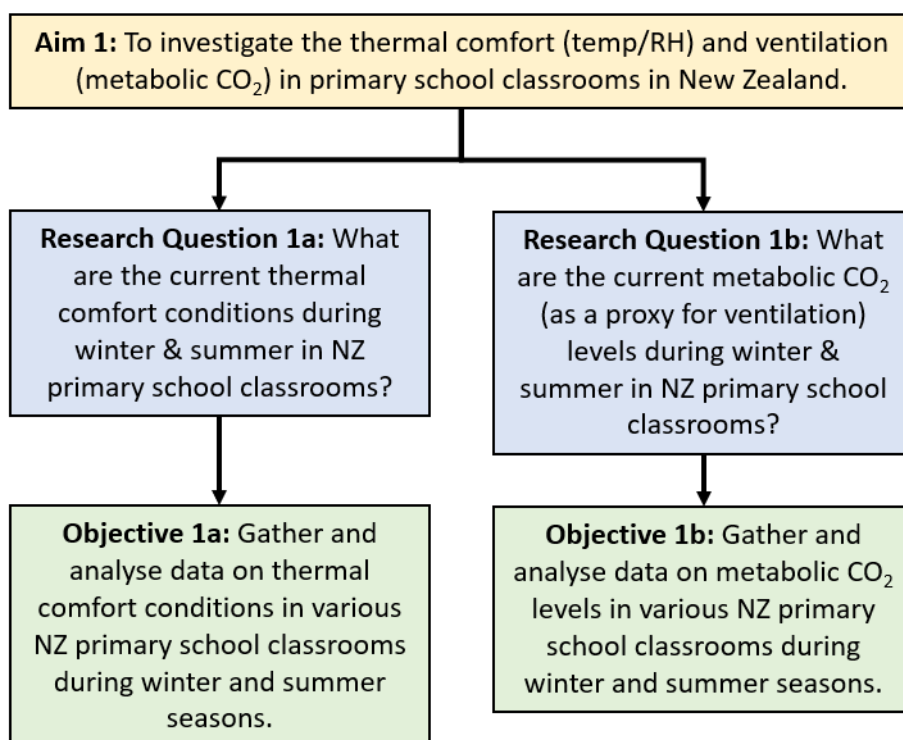
This concluding chapter aims to synthesise the findings of the previous chapters and provide an understanding of how the research objectives have been met. Each research goal will be discussed in detail, offering information on how the study outcomes align with the initial goals. By systematically addressing each aim, the PI will transition to overarching conclusions, drawing together the key lessons learned and their broader implications for educational practices and policies.

8.1 Achievement of study aims

8.1.1 Aim 1

Aim 1, as outlined in **Figure 8.1**, investigates the levels of thermal comfort (temperature and RH) and CO₂ (a proxy of ventilation) in primary school classrooms in NZ.

FIGURE 8.1: Outline of Aim 1



TC (temperature and relative humidity): Research question 1a was addressed by collecting data on temperature and RH in various classrooms. The analysis demonstrated seasonal variations, with specific areas identified for improvement, particularly in maintaining optimal TC during winter.

CO₂ (proxy for ventilation):

Research Question 1b focused on the efficacy of ventilation, monitored through CO₂ levels. The data revealed periods of effective ventilation, predominantly in summer, while highlighting occasional exceedances during winter that suggest a need for better ventilation management during the colder months.

The study has addressed the aims and objectives by providing detailed, season-specific data on TC&V conditions in NZ primary school classrooms. The findings highlight strengths and areas for improvement, offering actionable recommendations to maintain and improve TC&V standards. This analysis ensures that schools can take informed steps to foster a healthy and conducive learning environment year-round.

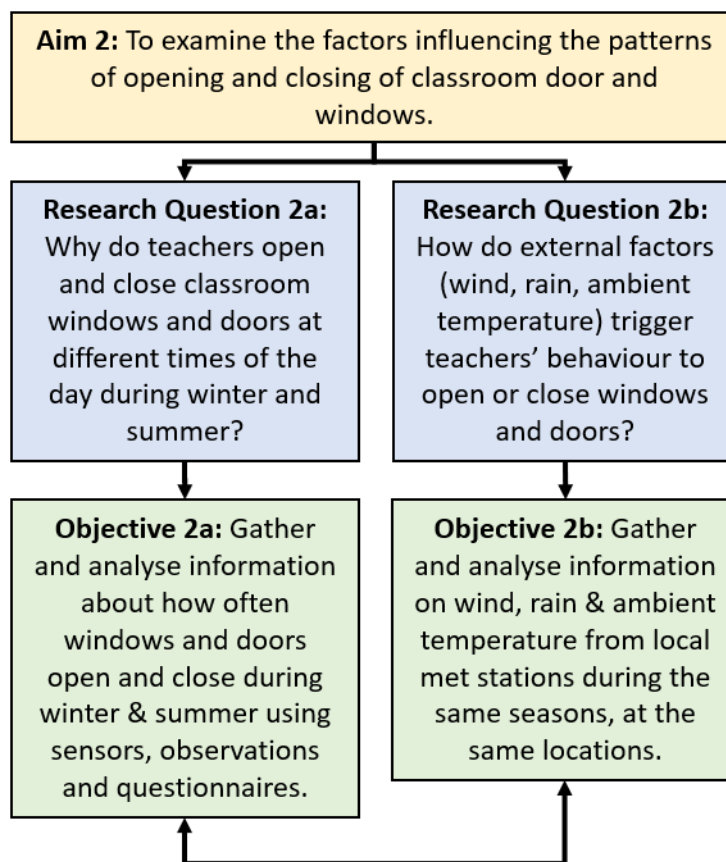
The analysis of classroom IEQ reveals a generally well-maintained environment with strong alignment to historical and contemporary research findings on primary school TC&V conditions. Classrooms perform admirably on most metrics and seasons, with specific areas of improvement identified, particularly in winter. Addressing issues through targeted improvements in heating and ventilation systems can further strengthen TC and air quality, ultimately fostering a more conducive learning environment. Schools can maintain optimal conditions throughout the year by continuously monitoring and adjusting the IEQ parameters and educating students and teachers about their importance.

The study on TC conditions and CO₂ levels in NZ primary school classrooms has met the stated aims and objectives. By systematically gathering and analysing data through IEM technology during winter and summer, this study provides insights into current IEQ conditions.

8.1.2 Aim 2

Aim 2, as outlined in **Figure 8.2**, examines the factors that influence the opening and closing patterns of classroom windows and doors.

FIGURE 8.2: Outline of Aim 2



To meet the aims, research questions, and objectives outlined for examining the factors influencing classroom window and door opening and closing patterns, the PI undertook a multi-faceted research approach combining sensor data, observations, and questionnaires alongside meteorological data collection.

Meeting Aim 2: Examine the factors that influence classroom window and door opening and closing patterns.

- Research Question 2a: Why do teachers open and close classroom windows and doors at different times during winter and summer?
- Objective 2a: Gather information about how often windows and doors open and close during winter and summer using sensors, observations, and questionnaires.

Steps taken:

1. **Use of sensors:** The PI installed magnetic sensors on classroom windows and doors to automatically log every instance of opening and closing. This continuous data collection spans the winter and summer terms, providing a detailed record of ventilation practices.
2. **Observational studies:** In addition to the sensor data, the PI conducted unannounced observational classroom visits. These visits aimed to capture real-time window and door-opening behaviours, ensuring an accurate juxtaposition with sensor data. Observing the same classrooms at various times throughout the day, the PI could directly note when and why windows and doors were adjusted, garnering insights into teachers' immediate motivations.
3. **Questionnaires:** Teachers received structured questionnaires to understand their perceptions, preferences, and the reasons behind their decisions to open or close windows and doors. These questionnaires were designed to gather qualitative data on perceived comfort, air quality, safety, noise, and temperature.

The combination of these methods provided a robust data set showing the frequency of window and door operations and the underlying reasons behind these actions. This mixed-method approach helped answer why teachers' behaviour differs significantly between different times of the day and seasons.

- Research Question 2b: How do external factors (wind, rain, ambient temperature) impact teachers' behaviour to open or close windows and doors?
- Objective 2b: Gather information on wind, rain, and ambient temperature from local met stations during the same seasons at the same locations.

Steps taken:

1. **Meteorological data collection:** The PI collected real-time weather data from local meteorological stations corresponding to the periods and locations where classroom window and door operations were monitored. These data included wind speed and direction, rainfall amounts, and ambient temperatures.
2. **Correlation analysis:** By aligning meteorological data with sensor logs and observational notes, the PI performed a correlation analysis to identify patterns and relationships between external weather conditions and teacher window and door opening behaviours. For example, the study could reveal trends such as windows that are closed during heavy rainfall or open more frequently on windy days for better ventilation.

3. **Sensor and weather data:** Integrating the environmental data with the sensor data allowed an understanding of how specific weather conditions directly affected opening and closing patterns. This integration made it possible to quantitatively measure the influence of factors such as wind speed, rain, and temperature fluctuations on ventilation decisions.
4. **Contextual observations:** During observational visits, the PI recorded contextual notes on weather conditions and their immediate impact on teacher ventilation actions. These qualitative data added depth to the numerical sensor data, allowing for a more nuanced understanding of behaviour in response to specific weather events.

Through this approach, the PI has met both objectives and aims. The research provided a view of why and how teacher behaviours around window and door operations vary across different times of the day and seasons (Research Question 2a). In addition, it clarified the impact of external meteorological factors on these behaviours (Research Question 2b).

Using a triangulated methodology:

- Quantitative data from sensors offered precise and objective measurements.
- Qualitative insights from observations and questionnaires provided context and rationale behind these behaviours.
- The weather data introduced an essential variable that influences the classroom environment.

This integrative approach ensured the reliability and depth of the findings, ultimately contributing to a more informed strategy to optimise classroom ventilation and ensure better IEQ in educational settings.

In conclusion, the interaction between meteorological conditions, window-opening behaviours, and IEQ in primary school classrooms provides valuable insights into optimising learning environments.

This study reveals several critical points supported by the existing literature and empirical observations. Firstly, seasonal variations play a significant role in influencing window-opening behaviours. During the colder months, the study

finds less frequent window openings, leading to poorer air quality due to elevated CO₂ levels. In contrast, increased window openings facilitate better ventilation and air quality in warmer periods, although they require balancing with TC to avoid overcooling or overheating.

Another key finding is the impact of teacher preferences on window-opening patterns. The study identified that individual teacher behaviour significantly influences the frequency with which windows are opened. Teachers who consistently maintain more open windows correlate with better IEQ. This highlights the need for teacher training and awareness of the importance of ventilation to maintain optimal IEQ.

The study also confirms that various environmental factors such as temperature, humidity, wind speed, rainfall, and cloud cover substantially determine the extent of window opening. This aligns with adaptive comfort models in the existing literature, which suggest that occupant behaviour adjusts to changing outdoor conditions to maintain comfort and air quality.

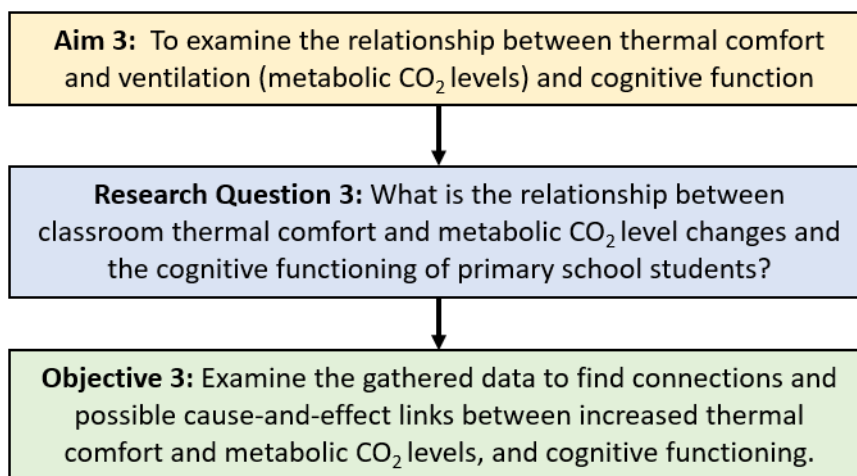
A significant advancement in this study is the technological integration of window and door sensors along with traditional observational methods. This dual approach provides an understanding of ventilation practices, which improves the reliability and precision of the data. The integration of these technologies supports more informed decisions about classroom ventilation strategies.

Maintaining good air quality is essential for health and cognitive performance. The study highlights the critical need for effective classroom ventilation to support student cognitive functions and overall health. The literature consistently emphasises the detrimental impact of high CO₂ levels on cognitive performance, reinforcing the importance of regular window openings to ensure a conducive learning environment.

8.1.3 Aim 3

Aim 3, as outlined in **Figure 8.3**, examines the relationship between TC and CO₂ levels and their impact on student cognitive function.

FIGURE 8.3: Outline of Aim 3



The PI has achieved Aim 3, which examined the relationship between TC, CO₂ levels, and cognitive function in primary school students. The following results summarise the methodological steps and findings that led to this achievement.

1. **Population dynamics:** The study incorporated primary school students who participated in cognitive tests, although there were occasional fluctuations in participation due to specific school activities. These variabilities were anticipated and managed to ensure robust data collection.
2. **Measurement tools:** Two air quality monitoring devices were used: the portable Q-Trak 7575 IAQ monitor for spot measurements during cognitive tests and a wall-mounted IEM unit for continuous monitoring. This dual approach ensured precise data collection on classroom environmental conditions.
3. **Data analysis techniques:** Data were analysed for homogeneity of variance using Levene's test and normality using the Shapiro-Wilk test. These tests confirmed the validity and reliability of the data, allowing for further robust statistical analyses such as ANOVA and Kruskal-Wallis tests.

Maintaining optimal indoor environmental conditions, specifically temperature and CO₂ is crucial for cognitive performance. The literature highlights the importance of staying within prescribed parameters to ensure comfort and cognitive efficiency. Data from Hawke's Bay schools indicate areas where temperature and CO₂ levels exceed recommended limits, potentially impairing cognitive functions. Schools

can create healthier and more productive learning environments by implementing better ventilation, climate control systems, and continuous monitoring and education.

Using robust data collection methods, thorough statistical analysis and nuanced interpretations of how environmental conditions affect cognitive performance, the PI answered the research question and met the objectives of Aim 3. This approach has provided valuable information on optimising indoor environments for better cognitive outcomes, highlighting the importance of well-managed TC and air quality in educational settings.

8.2 “So what”: Significance of the findings and recommendations

The “So What” part of the chapter represents the keystone of this journey. This section transcends the realm of facts and figures, venturing into the territory where implications emerge and broader narratives take shape. This section is not merely a conclusion; it is a conversation starter, challenging readers to connect the dots, and considering the wider implications of the work. Delving into this segment invites us to consider the broader context, asking what has been discovered, why it matters, and how it can influence understanding, decisions, and future endeavours.

8.2.1 Aim 1

The deployment of IEMs in various regions and seasons has provided valuable data that underscore the complexities of maintaining optimal TC&V in NZ primary school classrooms. The findings highlight significant seasonal disparities and the crucial role of building design, age, and ventilation strategies in the formation of IEQ.

To ensure that educational settings are conducive to learning and health, there is an urgent need for targeted interventions that include modern HVAC systems, improved natural ventilation practices, renovations of buildings, and the implementation of strategic policies. By addressing these critical areas, we can foster environments that

improve student well-being and academic performance.

All schools that participated in the study relied on natural ventilation. As such, several practical recommendations and some specific issues need to be considered to ensure a comfortable and healthy learning environment.

1. Temperature management

- *Winter:* Low temperatures (around 11.7 °C to 12.7 °C) mean reliance on natural ventilation could result in uncomfortable and cold classrooms. Strategies might include maximising sunlight during the day and using thermal mass to retain heat.
- Insulation and draught proofing: Improve insulation and duct insulation to maintain warmth and reduce energy consumption.
- *Summer:* Higher temperatures (around 19.7 °C to 20.1 °C) require efficient natural cooling strategies. Cross-ventilation and the use of cool night air to purge heat built up during the day can be effective.
- Consider using fans or mechanical ventilation (if available) if natural ventilation is inadequate.

2. Humidity control

- *Winter:* High humidity (around 83% to 84%) could lead to a damp environment conducive to mould growth. Ventilation should balance keeping heat and reducing humidity.
- *Summer:* Variable humidity levels (around 73% to 82%) require careful management to ensure comfort. Too much humidity can make it feel hotter than it is and too little can create a dry, uncomfortable atmosphere.

3. Rainfall and weather conditions

- *Rainy seasons:* Moderate rainfall (up to 8.4 mm in Summer) might require closing windows, which limits natural ventilation. Roof overhangs, louvres, or retractable awnings allow windows to remain open even during rain.
- *Variable conditions:* Understand and use prevailing wind patterns for optimal ventilation and ensure classrooms are protected from direct rain and adverse weather while allowing airflow.

4. Solar radiation and heat gain

- *Winter*: Lower solar radiation (85.8 to 122.1 kW/m²) suggests a need to maximise the heat gain from the Sun when available. The opening of the shades and the use of strategically placed windows can help warm the space naturally.
- *Summer*: High solar radiation (up to 263.3 kW/m²) can cause overheating. Proper shading devices, such as blinds, louvres, or reflective films, are essential to prevent excessive indoor heat gain.

5. Air quality and indoor environment

- *Ventilation rates*: Ensure that air exchange rates are sufficient to maintain good IEQ, considering occupancy levels and activities. Stagnant air can lead to increased levels of CO₂ and other pollutants.
- *Filtration*: Natural ventilation means that outdoor air quality must be monitored. Window screens or filters can help reduce the entry of pollutants and allergens.

6. Maintenance and cleanliness

- *Dust and pollen*: The open windows allow dust and pollen to enter, leading to allergies or respiratory problems. Regular cleaning and the use of filters can mitigate this.
- *Pest control*: Open windows and doors can increase the risk that pests enter classrooms. Using screens and proper sealing around windows can help prevent this problem.

7. Acoustic considerations

- *Noise pollution*: Natural ventilation often requires opening windows and doors, which can allow outside noise (traffic, playgrounds, etc.) to enter the classroom. This can disturb the learning environment. Acoustic treatments or strategic opening/closing of windows can help manage this.
- *Optimal swimming pool placement*: Noise mitigation is essential to maintain a conducive learning environment when planning swimming pool locations in educational environments. Avoid placing pools directly behind teaching venues to prevent noise disturbances. Instead, position them farther away

and incorporate buffer zones, such as green spaces, landscaped gardens, or administrative buildings, to dampen sound. Adding soundproofing materials within these buffer zones can further reduce noise transmission, promoting a balanced environment for both recreation and academics.

- *Priority over budget cuts:* When planning a new building or renovation, it is vital to maintain the integrity of the original budget for the acoustic design, even if overall costs begin to overrun. Acoustic design is crucial to ensure that the building serves its intended purpose. Compromising acoustic quality can lead to long-term issues such as poor sound insulation, increased noise pollution, and an uncomfortable environment for students and teachers. These problems can result in costly retrofits and decreased satisfaction, ultimately outweighing any short-term financial savings. Prioritising and preserving the budget for acoustic design ensures that the building remains functional, comfortable, and practical for its users.

8. Safety and security

- *Access control:* Open windows and doors can be a security concern. Ensure that there are measures to prevent unauthorised access when windows are open, especially when classrooms are not occupied.
 - *Fire safety:* Adequate ventilation should not compromise fire safety. Ensure that natural ventilation pathways do not interfere with fire exits and that all safety regulations are followed.
9. **Install thermostats:** Use programmable thermostats to maintain optimal classroom temperatures, adjusting settings based on occupancy and seasonal needs.
 10. **Regular maintenance:** Ensure that the heating, ventilation, and air conditioning systems (if applicable) are maintained regularly for optimal performance.
 11. **Monitor IEQ:** Regularly monitor IEQ parameters such as CO₂ levels, temperature, and humidity to ensure a healthy learning environment.
 12. **Educate students and staff:** Promote awareness among students and staff about the adjustment of clothing and behaviour (for example, closing curtains during hot days) to maintain comfort. Educating school staff and students about effective ventilation use (e.g. strategically opening windows during

breaks) and optimising occupancy rates can improve environmental conditions. Furthermore, policies advocating for reduced class sizes can alleviate CO₂ accumulation.

13. **Cross-ventilation design:** Ensure that classrooms are designed or arranged to maximise cross-ventilation, with windows and vents placed on opposite sides of the rooms.
14. **Flexible classroom layouts:** Arrange classrooms to maximise natural ventilation and passive heating/cooling options. This might include strategic placement of windows and doors.
15. **Adjustable openings:** Use windows and vents that can be adjusted to control the amount of airflow, allowing for flexible responses to varying weather conditions.
16. **Shading devices:** Implement shading devices like overhangs, louvres, or reflective films to manage solar gain while maintaining airflow.
17. **Thermal mass:** Use building materials with high thermal mass to stabilise indoor temperatures by absorbing heat during the day and releasing it at night.
18. **Roof ventilation:** Consider using roof vents or clerestory windows to remove the rising hot air, which is particularly important in the warmer months.
19. **Manual and automated controls:** While relying on natural ventilation, consider having some automated controls (like motorised windows) to optimise ventilation efficiently.

Schools can ensure a comfortable and conducive classroom learning environment by addressing considerations related to natural ventilation. By understanding and responding to seasonal variations, schools can improve airflow effectiveness, ultimately benefiting student well-being and academic performance throughout the year.

Practical implications and stakeholder involvement

The findings of this study have significant practical implications for various stakeholders, including school administrators, facility managers, policymakers, and parents.

1. **School Administrators and Facility Managers:** These stakeholders should prioritise the evaluations of their current HVAC systems (if applicable) and explore upgrades or replacements where necessary. Adopting monitoring tools, such as IEMs, for the continuous tracking of IAQ can guide timely maintenance and operational decisions.
2. **Policymakers:** Legislative frameworks should support funding for improvements in school infrastructure, focussing on sustainable practices, and integrating advanced building technologies. Policies that establish stricter standards for TC and IEQ in schools can drive accountability and improvements in the education sector.
3. **Parents:** Increased awareness among parents about the importance of IEQ and TC in schools can drive community advocacy for better learning environments, encouraging school administrations to adopt the necessary changes.

Collaborative efforts for improvements

Achieving optimal TC&V in primary school classrooms requires a concerted effort of various stakeholders. Collaborative initiatives that involve educational authorities, government bodies, researchers, and community members can drive systemic changes to sustain learning environments.

1. **Child-centric TC standards:** Global standards like ASHRAE and ISO tend to be designed for adults, with limited research specifically on children's TC needs. There is a need for standards that cater specifically to children's physiological and psychological differences, recognising their unique needs.
2. **Government and policy makers:** Government intervention is critical in setting standards and funding improvements in school infrastructure. Policies should prioritise:
 - *Mandatory monitoring:* Implementing regulations that mandate regular monitoring of the TC parameters and CO₂ levels to ensure compliance with health and safety standards.
 - *Funding for modernisation :* Allocating budgets for upgrading HVAC systems and improving the thermal efficiency of school buildings, especially older structures.

- *Green building incentives:* Providing incentives for schools to adopt green building practices and technologies that enhance environmental sustainability and IEQ.
3. **Educational authorities:** School boards and educational authorities play a crucial role in enforcing policies and implementing practical solutions.
- *Professional development:* Offering training programs for school staff on best practices for maintaining IEQ, including proper ventilation techniques and monitoring tools.
 - *Maintenance protocols:* Establishing regular maintenance schedules for HVAC systems and ensure that any identified problems are addressed promptly.
 - *Construction guidelines:* Incorporating guidelines for new school buildings that emphasise TC and effective ventilation as part of the design and construction process.
4. **Researchers and academic institutions:** Continued research is essential to address emerging challenges and develop innovative solutions.
- *Advanced studies:* Conducting in-depth research on the long-term impacts of TC and IAQ on students' health and cognitive performance to inform policy and practice.
 - *Technology development:* Developing and testing new technologies, such as smart HVAC systems and improved IAQ sensors, to enhance the monitoring and control of classroom environments.
 - *Knowledge sharing:* Facilitating knowledge exchange between researchers, policymakers, and practitioners through conferences, workshops, and publications.
5. **Community and parental involvement:** Engaging the broader community, including parents, can drive grassroots advocacy and support for better school environments.
- *Awareness campaigns:* Running awareness campaigns to educate parents and community members about the importance of TC and IEQ in schools.

- *Volunteer programs:* Initiating volunteer programs where parents and community members can contribute to monitoring efforts and maintenance activities.
- *Feedback mechanisms:* Establish channels for parents and students to provide feedback on indoor environmental conditions, ensuring that their voices are heard in decision-making processes.

8.2.2 Aim 2

1. **User-friendly mechanisms:** It is imperative to redesign window and door handles, fasteners, and locks to be more ergonomic, lightweight, and accessible, specifically for younger users. By focussing on ergonomic improvements, interactions with these components can become more intuitive and less strenuous, improving usability for individuals of all ages.
2. **Size considerations:** Besides general ergonomic enhancements, creating handles and mechanisms tailored for smaller hand sizes, such as children's, is crucial. Customizing the size and functionality of these features to accommodate children's needs can improve usability and safety, ensuring a more user-friendly experience.
3. **Tailored safety solutions:** Implement age-appropriate safety mechanisms and training to effectively address the diverse safety perceptions among different age groups. Design targeted training programs emphasizing safe practices when handling windows, considering varied safety needs and understanding levels across age groups.
4. **Ventilation and safety balance:** Develop windows that balance effective ventilation and security to address safety risks and ensure proper airflow without compromising safety. Introduce automated window systems and promote designs for enhanced airflow while preventing accidents or injuries, meeting both ventilation and safety requirements.
5. **Energy-efficient designs:** Design energy-efficient windows that minimise heat loss, reducing the need for additional heating and lowering energy consumption. Enhance thermal comfort within rooms to retain warmth during colder seasons, aligning with sustainability goals and cost savings.

6. **Odour control:** Incorporate features in windows to control odours and improve ventilation without affecting air quality. Implement sophisticated airflow management systems to maintain fresh air circulation and prevent stale odours, enhancing indoor environmental quality.
7. **Noise-reducing windows:** Develop noise reducing windows to minimise exterior disturbances and create a conducive learning environment. Enhance classroom activities by reducing outside noise, which is particularly beneficial in busy urban areas or high-traffic zones to promote focus and concentration.
8. **Training programs:** Conduct comprehensive training programs for teachers and students on optimal window and door usage for improved ventilation and comfort. Provide knowledge on maintaining temperature control, safety, and ventilation balance, enhancing learning outcomes and well-being.
9. **Clear guidelines:** Offer clear guidelines and best practices for managing window and door usage to maintain high indoor environmental quality. Provide practical noise reduction, safety, and odour management solutions, ensuring a comfortable and safe learning environment conducive to academic success. Implement awareness campaigns focusing on the benefits and safe window and door usage practices in educational settings.

By comprehensively addressing the diverse needs and challenges identified in the survey responses, educational institutions can create more user-friendly, safe, and comfortable classroom environments. Continuous feedback and iterative improvements will ensure that solutions remain practical and relevant to users' evolving needs across different age groups.

These recommendations aim to bridge the gap between current challenges and future possibilities, ensuring that window and door mechanisms in educational settings meet the diverse needs of teachers and students while advancing our understanding of their broader impacts on education and IEQ.

1. **Recommendations for policymakers and regulatory bodies:** Update and Enforce IEQ Standards: Ensure that standard guidelines such as those of ASHRAE and local health authorities are regularly updated to reflect the latest research on ventilation and IAQ, especially in educational settings. Implement regular inspections and monitoring programs to ensure that schools comply

with ventilation and IEQ standards. Provide support and resources for schools to meet these standards.

2. **Support research and development:** Fund studies on IEQ: Allocate funding for continued research on the impacts of IEQ on student health, comfort, and academic performance. Research should focus on identifying best practices for natural ventilation and integrating smart technologies.
3. **Promote innovation:** Encourage the development and adoption of new technologies in the school infrastructure that optimise ventilation and air quality, such as advanced sensor systems and automated windows.
4. **Encourage sustainable practices:** Incorporate Sustainability Goals: Mandatory requirement that new school buildings and renovations meet high sustainability standards, incorporating energy-efficient windows, passive ventilation techniques, and renewable energy sources.
5. **Educational programs:** Include sustainability and IEQ management in the school curriculum to raise awareness among students and promote healthy environmental practices from a young age.

Recommendations for Manufacturers and Designers

1. **Develop user-friendly ventilation products:** Design window mechanisms that are easy for all age groups, including children and teachers, considering ergonomic principles and accessibility. Create windows and doors that integrate automated controls, sensors, and environmental data feedback to optimise ventilation without compromising safety or usability.
2. **Tailored designs:** Develop window and door solutions specifically designed for educational environments, considering factors such as security, ease of use, and the diverse needs of students and teachers.
3. **Energy efficiency:** Focus on developing energy-efficient solutions that facilitate natural ventilation while minimising heat loss during the colder months and reducing the need for artificial cooling and heating.

Recommendations for schools and educational institutions

1. **Implement smart ventilation systems:** Install automated window systems with sensors to adjust opening and closing based on real-time environmental parameters such as temperature, humidity, CO₂ levels, and occupancy. Automation can help balance TC and air quality without relying solely on manual adjustments. Use weather forecasting data to pre-emptively adjust window operations. For example, windows could be programmed to open during favourable weather conditions and close in anticipation of rain or extreme temperatures.
2. **Provide training and awareness programmes:** Offer training sessions on optimal ventilation practices, highlighting the importance of balancing air quality and TC. Teachers should understand how to use windows and other ventilation methods effectively. Keep staff informed of the latest recommendations and strategies for maintaining good IEQ, especially in light of changing seasonal conditions or new health concerns.
3. **Enhance classroom design and infrastructure:** Ensure that windows are designed for easy operation and are strategically placed to promote cross-ventilation. Large, ergonomic, and easily accessible windows can facilitate better air circulation. Blinds, shades, or awnings can be used to control solar gain and provide comfort while allowing ventilation. Adjustable shading devices can help maintain an optimal indoor environment. Consider installing energy-efficient HVAC systems or air purifiers with adequate air exchange rates in classrooms where opening windows is insufficient or impractical.
4. **Adopt seasonal ventilation strategies:** Encourage opening windows during the warmest part of the day to allow for short bursts of fresh air without significantly lowering indoor temperatures. Use HVAC systems to maintain warmth while ensuring air quality. Keep the windows open to improve airflow and reduce indoor temperatures. Employ strategies such as opening windows in the early morning and late evening, while potentially using fans to improve air circulation. Adjust window operations according to daily temperature fluctuations, more frequent openings during mild temperatures, and less during cooler or more humid periods.

By implementing these recommendations, stakeholders at all levels can work together to improve IEQ in primary schools, ultimately improving students' and teachers' health, comfort, and performance.

8.2.3 Aim 3

Actionable steps: for Policy Makers

Implication: The study underscores the significant impact of environmental factors such as temperature, CO₂ levels, and relative humidity on students' cognitive performance.

1. **Regulation of IEQ:** Formulate and enforce policies to regulate and monitor classroom environmental conditions. Implement standards for optimal temperature, ventilation, and air quality in schools.
2. **Investment in infrastructure:** Allocate funding for advanced HVAC systems and quality air monitoring devices in schools to ensure consistent and safe learning environments.
3. **Teacher and administrator training:** Develop guidelines and training programs for school personnel on the effective management of classroom environments to enhance student learning outcomes.
4. **Scheduling reforms:** Advocate for testing and critical thinking tasks to be scheduled during times of the day when cognitive performance is typically higher, generally in the afternoon.

Actionable steps: for Educators:

Implication: The environmental conditions in the classroom can directly influence the cognitive abilities and overall performance of the students.

1. **Immediate environmental adjustments:** Regularly monitor classroom temperature and air quality. Use portable devices for spot checks during critical learning periods and adjust ventilation or heating accordingly.
2. **Optimal scheduling:** Align cognitively demanding activities with periods when students perform best, which may vary but generally suggests leaning toward afternoon sessions.

3. **Classroom management:** Incorporate routines that can mitigate environmental discomfort, such as allowing brief breaks for fresh air and ensuring proper hydration.
4. **Awareness and training:** Stay informed about the impact of environmental conditions on learning and incorporate strategies that address these factors to maximise student engagement and performance.

Actionable steps: for Parents:

Implication: The home and classroom environment plays a crucial role in the academic performance of children.

1. **Home environment:** Ensure that children have a comfortable and well ventilated study area at home, away from distractions and with optimal lighting and air quality.
2. **Engage with schools:** Stay involved and communicate with school administrators about the importance of maintaining good classroom conditions. Advocate for necessary improvements if conditions are suboptimal.
3. **Health and nutrition:** Support children's cognitive function by providing a balanced diet and ensuring that they stay hydrated, as physical well-being greatly influences cognitive performance.
4. **Structured routines:** Encourage consistent sleep schedules and morning routines that prepare children for a productive day, which can buffer against less favourable environmental conditions in schools.

Actionable steps: for the Community:

Implication: The broader community, including local businesses, health services, and civic organisations, plays a role in supporting educational environments that promote optimal cognitive performance among students.

1. **Community support initiatives:** Launch community-supported programmes to provide schools with the necessary resources to improve IEQ, such as funding advanced air filtration systems or providing portable air quality monitors.

2. **Health and wellness education:** Partner with schools to create educational programs focused on the importance of healthy living and its impact on student performance. This can include workshops on nutrition, exercise and the benefits of good IEQ.
3. **Volunteering:** Encourage community members to volunteer in schools to help maintain and monitor environmental conditions, such as helping to manage gardens or green spaces that can improve air quality.
4. **Local policy advocacy:** Advocate for local policies that support schools to maintain optimal learning environments. This could involve lobbying for funding, resources, and policies at school board meetings or other civic engagement channels.

This study highlights the importance of maintaining optimal indoor environmental conditions for cognitive performance in educational settings. By implementing these recommended actions, policymakers, educators, parents, and the community can collaboratively enhance the learning environment, thus improving student academic outcomes and overall well-being.

8.3 Future research directions

8.3.1 Aim 1

Based on the results of Chapter 5, several future research directions and practical applications can be identified.

1. **Occupant behaviour:** Research could focus on examining how the behaviour of students and staff influences indoor environmental conditions such as air quality, temperature, and noise levels. Researchers can develop and test interventions that optimise IEQ and TC in educational settings by understanding these behavioural patterns. Studies could explore the impact of habits like window opening, use of personal comfort devices, or location movement on the classroom environment and develop strategies to promote behaviours that enhance overall comfort and well-being.
2. **Traditional learning spaces vs modern learning environments:** Investigating the impact of traditional learning space designs, characterised by fixed seating

and a linear layout, versus modern learning environments with flexible seating and interactive technology. Studies could explore how adaptable layouts and integrated technology in modern settings improve comfort and learning outcomes compared to more static, traditional classrooms.

3. **Single cohorts vs. mixed cohorts:** Examining how the composition of student groups—single cohorts (students of the same age or educational level) versus mixed cohorts (students of varying ages and educational backgrounds)—influences TC and IEQ. Research could assess the specific environmental needs and preferences of each type of cohort and the challenges and benefits associated with maintaining optimal IEQ in these different settings. Findings can inform tailored strategies to enhance comfort and productivity in diverse educational environments.
4. **Impact of fidgeting on TC and IEQ:** Investigating how student behaviours, specifically fidgeting in their seats, impact TC and IEQ in learning environments. Research could focus on understanding the physiological and psychological reasons behind fidgeting and how different classroom settings can mitigate or exacerbate this behaviour. By examining variables such as seat design, classroom layout, and temperature regulation, studies can identify strategies to create environments that reduce discomfort and allow students to concentrate better.
5. **Ergonomics and classroom design:** Assessing the role of ergonomic seating and furniture design in minimizing the need for fidgeting and its effects on TC and IEQ. Research could explore how ergonomic improvements, such as adjustable chairs and desks, influence student behaviour and overall comfort. These studies could provide insights into optimal classroom furniture and layout designs that accommodate natural movement, enhance comfort, and improve learning outcomes.
6. **Extended longitudinal studies:** Further longitudinal studies are needed to evaluate the sustained impact of implemented interventions on IAQ and TC over multiple years.
7. **Expanded geographic scope:** Expanding the geographic scope to include more diverse climatic regions within NZ and internationally can provide a better understanding of the challenges and practical solutions.

8. **Advanced technology integration:** Future research can explore the integration of emerging technologies such as smart sensors, real-time monitoring systems, and machine learning algorithms for predictive maintenance and control of HVAC systems.
9. **Holistic environmental assessment:** Incorporating assessments of other IEQ parameters, such as particulate matter, volatile organic compounds (VOCs), and biological contaminants, can provide a more holistic understanding of the indoor environment.
10. **Student health and performance Metrics:** Correlating environmental data with detailed health and cognitive performance metrics of students can strengthen the evidence base for the importance of maintaining optimal indoor conditions.

8.3.2 Aim 2

Based on the results of Chapter 6, several future research directions and practical applications can be identified:

1. **Child-specific standards:** Despite the fact that current standards predominantly focus on adults, our study highlights the need for child-specific IEQ guidelines. Future research can investigate in more depth the development of these standards, considering the unique physiological and psychological characteristics of children.
2. **Enhanced ventilation strategies:** The findings advocate for improved window design and maintenance practices that facilitate easier opening, helping teachers better manage ventilation without compromising TC.
3. **Energy-efficient heating and cooling:** Highlighting the role of inverter heat pumps, the study suggests a more balanced use of mechanical and natural ventilation to improve IEQ while maintaining energy efficiency. Future research could explore integrating smart systems with adaptive control that responds to real-time environmental data.
4. **Education and awareness:** There is a clear need for greater awareness and training of teachers and staff on best practices for managing IEQ, balancing mechanical systems with natural ventilation methods, and understanding the impacts on student health and performance.

5. **Longitudinal studies:** There is a gap in longitudinal studies that examine the long-term health and academic impacts of sustained poor IEQ. Future research could track these results over extended periods, providing more robust data to inform policy and practice.

The study contributes significantly to understanding IEQ in primary school classrooms in NZ and fits well within the broader context of international research. By focussing on specific behaviours like window opening and inverter heat pumps, practical insights are provided that can be directly applied to improve classroom environments. This targeted approach fills existing knowledge gaps, particularly in NZ-specific contexts, and lays the foundation for future research to develop more nuanced and effective IEQ management strategies.

1. **Gender distribution:** The gender distribution could point to the need for additional research to address any potential differences in TC&V requirements or window-opening behaviours between different genders or within more balanced gender distributions in other professions or contexts.
2. **Behavioural analysis:** Conduct longitudinal studies to understand long-term patterns and changes in window and door usage among different age groups of teachers. This can provide insights into how behaviours evolve and inform more effective design and training interventions.
3. **Innovative solutions:** Explore the development and implementation of advanced ventilation technologies that balance fresh air intake with energy efficiency, such as automated window opening systems that respond to CO₂ levels, temperature, and occupancy.
4. **Child-friendly designs:** Investigate the interaction of students with window mechanisms and safety features, ensuring designs are not only accessible but also safe for frequent use by children. This can include studies on student strength, skill, and safety awareness.
5. **Cost-benefit analysis:** Perform cost-benefit analysis of the implementation of new designs and technologies to assess financial feasibility and long-term benefits for schools, including potential energy savings and improved student and teacher performance.

6. **Cognitive function research:** Study the specific impact of external noise on cognitive functions and learning outcomes. Understanding this can help prioritise noise mitigation in window designs and classroom layout planning.
7. **Future-proof designs:** Explore how window and door designs can be adapted to withstand extreme weather events due to climate change, ensuring stable and comfortable classroom environments under varying conditions.
8. **Targeted training programs:** Develop training for teachers on the importance of ventilation and best practices in various weather conditions.
9. **Automated ventilation systems:** Explore the implementation of automated window systems that respond to real-time environmental data to optimise ventilation and maintain IEQ.
10. **Continuous monitoring:** Enhance the use of advanced sensor technology to provide ongoing feedback on IEQ, ensuring timely interventions when necessary.
11. **Customised ventilation solutions:** Design classroom ventilation strategies that are tailored to specific climatic conditions and structural characteristics to maximise efficiency and comfort.

8.3.3 Aim 3

Based on the outcomes of Chapter 7, several future research directions and practical applications can be identified:

1. For an overview of the ongoing research that has emerged from this section of the study, refer to **the appendix I**.
2. **Optimizing learning environments:** Consistent monitoring and management of temperature and CO₂ levels are essential to ensure optimal cognitive performance and comfort in educational settings. Natural ventilation should be prioritised as it promotes a conducive learning environment.
3. **Detailed room-specific analysis:** Future research should focus on refining test methods and expanding investigations to understand better room-specific nuances and the interplay between different environmental factors and cognitive performance. Understanding the complex mechanisms behind the

observed variability in sensitivity to temperature and CO₂ changes down to individual classroom characteristics, such as layout, ventilation systems, and teaching dynamics.

4. **Task-specific sensitivities:** Further exploration of why specific cognitive tasks are more affected by TC and CO₂ levels can help to tailor classroom environments to support specific educational activities. For example, tasks that require significant cognitive flexibility and working memory might benefit from more stringent environmental controls.
5. **Time-of-day considerations:** The impact of time of day on cognitive function suggests the need to schedule cognitively demanding tasks when students are likely to perform best, which typically appears to occur in the afternoon based on the findings of this study. More nuanced studies could pinpoint optimal times for different types of cognitive activities.
6. **Broader applications:** The insights of this study apply beyond educational settings, such as optimising office environments and developing policies for better IEQ in various public spaces. Integrating findings into smart building technologies could improve the real-time management of HVAC systems and environmental sensors, improving overall comfort and productivity.

8.4 Call to action

Ensuring that our school environments are conducive to learning and health is a shared responsibility. The PI calls on policymakers, educational authorities, researchers, school administrators, teachers, parents, and the broader community to:

- Advocate for and implement policies prioritising investments in school infrastructure and IEQ improvements.
- Utilize innovative technologies and strategies to monitor and improve IEQ continuously.
- Engage in collaborative efforts to share knowledge, resources, and best practices to create healthier and more comfortable learning environments.

By working together, we can create a future in which every child can access a learning environment that supports their health, well-being, and academic success.

The journey toward better school environments is ongoing and our collective responsibility is to ensure that we are making strides in the right direction.

Chapter 9

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Appendix A

Statements of contribution

Tookey, L., Boulic, M., Phipps, R., & Wang, Y. (2019). *Air stuffiness index and cognitive performance in primary schools in New Zealand*. Proceedings - Healthy Buildings 2019 Asia and Pacific Rim (HB2019 Asia). Changsha, China: Healthy Buildings 2019 Asia



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STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Lara Tookey		
Name/title of Primary Supervisor:	Dr Mikael Boulic		
In which chapter is the manuscript /published work:	Appendix A		
Please select one of the following three options:			
☒ The manuscript/published work is published or in press • Please provide the full reference of the Research Output: Tookey, L., Boulic, M., Phipps, R. & Wang., Y. (2019). Air stuffiness index and cognitive performance in primary schools in New Zealand. Paper presented at Healthy Buildings 2019 Asia Conference, Changsha, China.			
☐ The manuscript is currently under review for publication – please indicate: • The name of the journal: • The percentage of the manuscript/published work that was contributed by the candidate: 75.00 • Describe the contribution that the candidate has made to the manuscript/published work: L. Tookey authored the paper utilizing data gathered by Y. Wang. The other co-authors contributed by reviewing the manuscript and providing valuable input.			
☐ It is intended that the manuscript will be published, but it has not yet been submitted to a journal			
Candidate's Signature:	Lara Tookey Digitally signed by Lara Tookey DN: cn=Lara Tookey, c=NZ, o=SBE, ou=Massey University, email=tookey@massey.ac.nz Reason: Acceptance Date: 2021.07.26 11:44:00 +1200		
Date:	26-Jul-2021		
Primary Supervisor's Signature:	Mikael Boulic Digitally signed by Mikael Boulic DN: cn=Mikael Boulic, c=NZ, o=Massey University, ou=SBE, email=m.boulic@massey.ac.nz Date: 2024.05.20 11:20:01 +1200		
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Thank you for your email. We are located on the East Coast of the United States which is the reason for the delay in responding. I received your email below and your email related to Healthy Buildings Asia 2019. You have our permission to included in your thesis.

Please let us know if you need any further documentation or proof of attendance.

Our best,



SARAH LARSEN MILLER

ISIAQ Secretariat

c/o Infinity Conference Group, Inc.

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From: Lara Tookey <L.Tookey@massey.ac.nz>

Sent: Sunday, March 17, 2024 6:22 PM

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Subject: 2nd request for copyright release.

Greetings

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Boulic, M., Wang, Y., Phipps, R., Chitty, C., Cunningham, C., Moses, A., Weyers, R., Jang-Jaccard, J., Olivares, G., Shekar, A., Longley, I., **Tookey, L.**, Ponder-Sutton, A. and the Healthy School Research

Tookey, L., Boulic, M., McDonald, B., Page, W., Wargocki, P., van Heerden., (2023). *Ventilation reliability: A pilot study on window opening behaviour in a primary school*. Paper presented at 43rd AVIC – 11th TightVent & 9th Venticool Conference, Copenhagen, Denmark.

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Lara Tookey Digitally signed by Lara Tookey DN: cn=Lara Tookey, c=NZ, o=School of Built Environment, ou=Massey University, email=l.tookey@massey.ac.nz Date: 2024.02.27 16:11:20 +13'00' 27-Feb-2024 Mikael Boulic Digitally signed by Mikael Boulic DN: cn=Mikael Boulic, c=NZ, o=Massey University, ou=SBE, email=m.boulic@massey.ac.nz Date: 2024.05.20 11:22:16 +12'00'	

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RE: AIVC 2023 | Conference Book of Proceedings and Presentations

Maria Kapsalaki <maria.kapsalaki@inive.org>

Fri 2024-03-22 21:19

To: Lara Tookey <L.Tookey@massey.ac.nz>

Cc: registrations@aivc2023conference.org <registrations@aivc2023conference.org>

Dear Lara,

I hope you are doing well.

You do have our consent to include your paper in your PhD thesis.

Good luck with your thesis presentation!

Kind Regards,
Maria Kapsalaki
Senior Consultant
INIVE

From: Lara Tookey <L.Tookey@massey.ac.nz>

Sent: Monday, March 18, 2024 12:16 AM

To: AIVC 2023 <registrations@aivc2023conference.org>

Subject: Re: AIVC 2023 | Conference Book of Proceedings and Presentations

Dear Maria

I had the pleasure of presenting a paper and poster at the conference last year. I am now in the process of compiling my PhD for examination and would like to include this paper.

I would like to obtain consent to include this paper in my PhD thesis. Could you please let me know who I need to contact in order to achieve this.

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Many thanks
Lara

From: EventsAir <no-reply@eventsairmail.com> on behalf of AIVC 2023 <mail@eventsairmail.com>

Sent: Saturday, October 28, 2023 00:07

To: Lara Tookey <L.Tookey@massey.ac.nz>

Subject: AIVC 2023 | Conference Book of Proceedings and Presentations

Tookey, L., Boulic, M., Page, W., Wargocki, P., van Heerden. A. (2024). *A Pilot Study on Window Opening Behaviour in Auckland, New Zealand*. *REHVA Journal*. 02: 25-29



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Date:	27-Feb-2024
Primary Supervisor's Signature:	Mikael Boulic Digitally signed by Mikael Boulic DN: cn=Mikael Boulic, c=NZ, o=Massey University, ou=SBE, email=m.boulic@massey.ac.nz Date: 2024.05.20 11:19:02 +12'00'
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Lara Tookey

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Sent: Wednesday, 5 June 2024 11:02 pm
To: Lara Tookey
Subject: RE: AIVC 2023 Conference- Selected paper for REHVA special issue

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Dear Lara,

You are allowed to include or refer to the article we published if you include the reference to our journal <https://www.rehva.eu/rehva-journal/chapter/a-pilot-study-on-window-opening-behaviour-in-auckland-new-zealand>

Beste Regards,
Jaap Hogeling MSc
Fellow of ASHRAE and REHVA

Editor-in-Chief REHVA Journal

REHVA Federation of European Heating, Ventilation and Air-conditioning Associations
 rue Washington 40, 1050 Brussels - BELGIUM
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From: Lara Tookey <L.Tookey@massey.ac.nz>
Sent: Wednesday, June 5, 2024 3:51 AM
To: Jaap Hogeling | ISSO <j.hogeling@isso.nl>
Subject: RE: AIVC 2023 Conference- Selected paper for REHVA special issue

U ontvangt niet vaak e-mail van l.tookey@massey.ac.nz. [Meer informatie over waarom dit belangrijk is](#)

Greetings Jaap

The paper looks wonderful – thank you.

I am in the process of compiling my PhD for examination and would like to include this paper.

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Looking forward to hearing from you.

Many thanks
Lara

Lara Tookey

MCM; PgDipEd; GDipHE; PgDipMan; BSc(QS)

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Candidate's Signature:	Lara Tookey Digitally signed by Lara Tookey DN: cn=Lara Tookey, c=NZ, o=School of Built Environment, ou=Massey University, email=l.tookey@massey.ac.nz Date: 2024.02.27 16:02:37 +13'00'		
Date:	27-Feb-2024		
Primary Supervisor's Signature:	Mikael Boulic Digitally signed by Mikael Boulic DN: cn=Mikael Boulic, c=NZ, o=Massey University, ou=SBE, email=m.boulic@massey.ac.nz Date: 2024.05.20 11:19:02 +12'00'		
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Wed 2024-03-20 02:36

To: Lara Tookey <L.Tookey@massey.ac.nz>

Dear Lara,

Our pleasure. You have permission to use your Indoor Air 2018 conference paper as well.

Please let us know if you have any questions.

My best,



SARAH LARSEN MILLER

ISIAQ Secretariat

c/o Infinity Conference Group, Inc.

Phone: 703.925.9455

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From: Lara Tookey <L.Tookey@massey.ac.nz>

Sent: Monday, March 18, 2024 6:49 PM

To: info@isiaq.org

Subject: Re: 2nd request for copyright release.

Greetings Sarah

Many thanks for getting back to me, and for your permission for the Healthy Buildings Asia 2019.

I did also send you another request - INDOOR AIR 2018, the 15th Conference of the International Society of Indoor Air Quality and Climate (ISIAQ), Pennsylvania Convention Center, Philadelphia, Pennsylvania, 22 – 27 July (details below).

Could you please confirm if I have your permission to include this one in my thesis as well.

Best wishes, from the opposite side of the world.

Lara

From: info@isiaq.org <info@isiaq.org>

Sent: Tuesday, March 19, 2024 06:51

To: Lara Tookey <L.Tookey@massey.ac.nz>

Subject: RE: 2nd request for copyright release.

Dear Lara,

Boulic, M., Wang, Y., Phipps, R., Chitty, C., Cunningham, C., Moses, A., Weyers, R., Jang-Jaccard, J., Olivares, G., Shekar, A., Longley, I., **Tookey, L.**, Ponder-Sutton, A. and Waters, D. (2019). *Project: Using a low-cost sensor platform to explore the indoor environment in New Zealand schools*. BRANZ Research Now: Indoor air quality #5



GRADUATE
RESEARCH
SCHOOL

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Lara Tookey
Name/title of Primary Supervisor:	Dr Mikael Boulic
In which chapter is the manuscript /published work: Appendix A	
Please select one of the following three options:	
☒ The manuscript/published work is published or in press • Please provide the full reference of the Research Output: Boulic, M., Wang, Y., Phipps, R., Chitty, C., Cunningham, C., Moses, A., Weyers, R., Jang-Jaccard, J., Olivares, G., Shekar, A., Longley, I., Tookey, L., Ponder-Sutton, A. and Waters, D. (2019). Project: Using a low-cost sensor platform to explore the indoor environment in New Zealand schools. BRANZ Research Now: Indoor Air Quality \#5	
☐ The manuscript is currently under review for publication – please indicate: • The name of the journal: • The percentage of the manuscript/published work that was contributed by the candidate: 10.00 • Describe the contribution that the candidate has made to the manuscript/published work: L. Tookey contributed by helping to edit the paper	
☐ It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Lara Tookey Digitally signed by Lara Tookey DN: cn=Lara Tookey, c=NZ, o=School of Built Environment, ou=Massey University, email=L.Tooley@massey.ac.nz Date: 2024.02.27 16:02:37 +13'00'
Date:	27-Feb-2024
Primary Supervisor's Signature:	Mikael Boulic Digitally signed by Mikael Boulic DN: cn=Mikael Boulic, c=NZ, o=Massey University, ou=SBE, email=m.boulic@massey.ac.nz Date: 2024.05.20 11:19:02 +12'00'
Date:	

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/publication or collected as an appendix at the end of the thesis.

Still waiting for response to email

Appendix B

Further research engagement

Further research involvement and dissemination thereof is detailed below in chronological order:

Learning Environments Australasia (LEA) Conference

- Date: 28 May 2019
- Activity: I participated in the LEA conference in Perth to disseminate my research agenda.

Global Schools NZ Convention

- Date: 10 September 2019
- Activity: The principal of the school where I conducted my pilot study invited me to present my research at the Global Schools NZ convention. Global Schools operate under the auspices of the UN Sustainable Development Solutions Network (SDSN), offering a program designed for primary and secondary education. They provide resources and backing for schools, educators, and researchers to infuse principles of sustainable development into educational practices, extending from classroom activities to policy formulation.

Research funding - Lottery Health Research Equipment

- Date: 1 January 2020
- Activity: I successfully composed a grant proposal for Lottery Health Research, securing NZ\$ 60,000 in funding. With this financial support, EEG headsets and laptops were purchased to conduct cognitive assessments. In light of COVID-19 safety measures, extra consumables were bought to ensure each participant had their own EEG accessories rather than sharing them with others.

Research funding - MURF

- Date: 1 January 2020
- Activity: I developed a grant application for the Massey University Research Funding, requesting NZ\$11,811. The grant was approved, with an award of NZ\$10,000. The allocated funds were used for licensing EmotivPro professional software, procuring cognitive tests, supporting field studies, and covering conference travel and accommodation expenses.

Interaction with Auckland Emergency Response Team as Massey Sensory Lab

- Date: 14 July 2020
- Activity: I jointly facilitated the Auckland Emergency Response Team gathering at the Massey Sensory Lab.

Fulbright - Visiting Student Researcher Application

- Date: July - September 2020
- Activity: I was delighted to receive an invitation from the Center for the Built Environment Research Institute at the University of California, Berkeley, for a tenure extending over ten months starting in August 2021. This prestigious opportunity inspired me to simultaneously apply for the Fulbright Visiting Student Researcher Program to fund and add an international dimension to my research stay. Throughout the application, I was actively involved in the selection process, which involved shortlisting and multiple interviews to gauge my aptitude and research goals. The process concluded with the final interview, held on September 18th, 2020, at 3:00 PM, where I was one of the last ten candidates standing, hoping to secure the position and the Fulbright support. Regrettably, amid the challenges posed by COVID-19 and the formidable calibre of my nine fellow candidates, my application was unsuccessful. As a postdoctoral fellow, the intention is to make another attempt, given that our research interests remain closely aligned.

Learning Environments Local Branch Conference

- Date: 26 November 2020
- Activity: I presented the research at the Learning Environments Local Branch Conference in New Zealand.

25th International Clean Air and Environment Conference (CASANZ 2021)

- Date: 17 May 2021
- Activity: I presented the research to a broader Australasia audience during an online conference session.

Research funding - French Research Related Project (F2RP)

- Date: 1 January 2022
- Activity: I submitted a proposal to the French Embassy in New Zealand in response to their call for French Research-Related Project proposals. The application was approved, and the PI received NZ\$6,000. These funds were utilised to procure extra cognitive tests and buy thank-you vouchers for the schools after the research data collection.

Guest Researcher at Technical University of Denmark

- Date: 25 September - 6 October 2023
- Activity: I was invited by Associate Professor Pawel Wargocki to serve as a guest researcher at the Technical University of Denmark (DTU). Here I presented an overview of the research agenda to the Department of Environmental and Resource Engineering at DTU.
- Activity: The PI participated in Annex 86 workshops.
- Activity: The PI delivered a paper and poster presentation at the 43rd AIVC Conference
- Activity: The PI established contact with Franck Lucas from Université de la Polynésie Française, Laboratoire GEPASUD.

PhD Study Leave in France

- Date: 6 October - 19 October 2023
- Activity: I was invited by Dr. Gaëlle Guyot as a guest researcher with the **Building Performance and Energy (BPE) team at Cerema, L'Isle d'Abeau**. During the visit, I delivered a research presentation to the High-Performance Building Team at Cerema and conducted interviews with key Applied Psychology Research (Psycap) team members.

- Activity: I also collaborated with other PhD students and presented the research to faculty, staff, and students at the **Building Energy Processes Laboratory (LOCIE) at the University of Savoie Mont Blanc**.
- Date: 23 October 2023
- Activity: Visited **Campus Etoile - Site Saint Jérôme Marseille**
 - I met with Mathilde Favier, Jonathan Mirault and Nicolas Mascret, who are part of the Inspé team (Institut National Supérieur du Professorat et de l'Éducation). They form part of the larger AMPIRIC network.
 - AMPIRIC (the "Aix-Marseille Partners for Innovation, Research, and Industrial Collaboration") is an initiative Aix-Marseille University hosts to foster innovation, research, and industrial collaboration in various disciplines. The program seeks to unite researchers, industry professionals, and academic institutions to create a synergistic environment for scientific and technological advancements.
 - The Inspé team typically focuses on the training and development of future educators in France.
 - The idea was to establish a collaboration with the Inspé team. The collaboration aims to leverage their unique educational training and development position to undertake cutting-edge EEG (electroencephalography) research with their teaching cohort. The proposed study will involve monitoring and analysing the brain activity of both student teachers and experienced educators during various teaching and learning activities. This partnership aims to achieve several objectives:
 1. **Data collection:** By involving the Inspé team, the research could benefit from a diverse and large sample size of educators, enhancing the data's robustness and applicability.
 2. **Practical insights:** The collaboration would provide practical insights into how cognitive and neural processes underpin teaching practices and learning experiences. Understanding these can help improve teaching methods and educational outcomes.
 3. **Interdisciplinary collaboration:** Combining expertise from the fields of education and neuroscience could foster innovative educational strategies that are informed by empirical brain data.

4. **Shared resources and expertise:** Both parties could share resources and expertise, optimising the research process and outcomes.
 5. **Global knowledge exchange:** The data collected would be shared with the PI based in NZ, promoting global knowledge exchange and collaborative research practices. This would enhance the study's international impact and pave the way for future cross-border research collaborations.
- By merging the practical teaching environment of the Inspé team with advanced EEG research methodologies, the collaboration hoped to yield valuable data and insights that could significantly advance the field of educational neuroscience. Ultimately, the shared findings would aim to innovate and improve teaching methodologies, benefiting educators and students alike across the globe.

- Date: 31 October 2023 - **AIRPARIF**
- Activity: Meeting - **Airlab Microsensor Challenge and "Aérons" Project CO₂ Sensors in Paris Schools**
 - I met with Juliette Laurent, International Relations Coordinator; François Gaie-Levrel, Research Coordinator; and Arnaud Deschamps, AIRLAB Coordinator.
 - AIRPARIF created a beneficial site <https://airlab.solutions/en/projets/challenge-microcapteurs-edition-2023-189> which hosts the outcomes of the AIRLAB Microsensors Challenge. This provides a robust and independent evaluation of the performance of microsensors under real conditions to provide a decision-support tool for potential users.
 - Juliette presented the Aérons project. A key outcome of the study in middle schools highlighted the issue of sensor ownership, as most teachers do not have an assigned classroom. Initial findings indicated a significant concern regarding classroom ventilation; however, 80% of participants reported ventilating frequently. While most participants believed their ventilation practices were sufficient, 20% felt they were over-ventilating.
 - By the end of the project, participants reported an increase in their ventilation frequency, guided by the CO₂ sensors. Notably, 57% of participants indicated they had altered their ventilation practices due to the sensors' data. Overall, the participants were satisfied with the experiment; they found the sensors easy to use, and 87% expressed a desire to keep them. Many were surprised by how quickly CO₂ levels rose above the threshold and how long it took to bring them back down through ventilation.
 - After presenting my study to the team, we all headed out for lunch.
- Date: 3 November 2023 - **Public Health France**
- Activity: **Meeting with Marion Hulin and Professor Frank Ramus**
 - I met with Marion Hulin, Scientific Project Manager at Santé Publique France, and Professor Frank Ramus, Research Director at CNRS. Professor Ramus leads the "Cognitive Development and Pathology" team within the Laboratory of Cognitive Sciences and Psycholinguistics at the École

Normale Supérieure in Paris. A doctoral student and a master's student were also in attendance.

- Marion Hulin began the meeting by providing an overview of Santé Publique France and its Department of Environmental and Occupational Health (DSET). Their mission focuses on producing and analysing evidence-based data to understand the links between environmental factors (both general and occupational) and human health. One primary focus is bringing IEQ-related health issues to the forefront of public debate, aiming to better protect people by collaborating with the French Observatory of Indoor Air Quality.
- Following Marion's presentation, Florine Menzri shared her meta-analysis research on the relationship between classroom air quality and children's academic performance. Her key observations included:
 - * Methodological heterogeneity among studies.
 - * Diverse definitions of health and environmental indicators.
 - * Lack of standardisation in measuring performance changes relative to CO₂ variations.
 - * Non-standardised results.
 - * Insufficient demonstration of biological plausibility.
 - * Unresolved questions regarding the specific effects of CO₂ versus its role as an indicator of IAQ.
- Florine's study served as a precursor to the research that Professor Ramus and his student, François Trublereau, were about to present. They are investigating climate change's impact, particularly heat's short-term effects, on children's cognitive abilities in schools. Their study is based on the work of Park, Goodman, and Behrer (2021) and involves an 11-year longitudinal and observational research project conducted in France.
- The PI presented her research again and gathered valuable feedback from the attendees.

Pacific Fund co-funding application - TROPIC

- Date: 22 November 2023
- Activity: I am coordinating with Franck Lucas from Université de la Polynésie Française, Laboratoire GEPASUD and Dr Mikael Boulic from Massey University

to write an application, “Passive cooling of Polynesian schools in a context of climate change: thermal comfort, air quality, cognitive health and reduction of electrical consumption”. TROPIC - Thermal Research fOr Pacific Island Classrooms

Initiation of SmartBREATH project

- Date: 27 November 2023
- Activity: 1st meeting of SmartBREATH consortium - **Smart** and resilient Buildings for impRoved Energy, Air qualiTy, Health and comfort in a climate change context. The French National Agency has earmarked the project for Research to develop an in-depth proposal for additional funding. The PI is coordinating closely with CEREMA, represented by Dr. Gaëlle Guyot.

2023 AUBEA and EPPM Conference

- Date: 29 November 2023
- Activity: At the 2023 Built Environment Research workshop and Poster presentation, the PI showcased the research and received the Best Poster (Content) Award.

Appendix C

Ethics applications

Human Ethics Notification - 4000021288

humanethics@massey.ac.nz <humanethics@massey.ac.nz>

Fri 2019-08-09 14:46

To: Lara Tookey <L.Tookey@massey.ac.nz>; Mikael Boulic <M.Boulic@massey.ac.nz>; Phipps, Robyn <R.A.Phipps@massey.ac.nz>

Cc: Human Ethics <gmhumeth@massey.ac.nz>

HoU Review Group

Ethics Notification Number: 4000021288

Title: Case studies on light quality of classrooms in New Zealand

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Professor Craig Johnson, Director (Research Ethics), email humanethics@massey.ac.nz.
"

Please note that if a sponsoring organisation, funding authority or a journal in which you wish to publish require evidence of committee approval (with an approval number), you will have to complete the application form again answering yes to the publication question to provide more information to go before one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

You are reminded that staff researchers and supervisors are fully responsible for ensuring that the information in the low risk notification has met the requirements and guidelines for submission of a low risk notification.

If you wish to print an official copy of this letter, please login to the RIMS system, and under the Reporting section, View Reports you will find a link to run the LR Report.

Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)

Human Ethics Notification - 4000021332

humanethics@massey.ac.nz <humanethics@massey.ac.nz>

Wed 2019-06-26 09:25

To: Lara Tookey <L.Tookey@massey.ac.nz>; Mikael Boulic <M.Boulic@massey.ac.nz>; Phipps, Robyn <R.A.Phipps@massey.ac.nz>;

Wyatt Page <W.H.Page@massey.ac.nz>

Cc: Human Ethics <gmhumeth@massey.ac.nz>

HoU Review Group

Ethics Notification Number: 4000021332

Title: Case studies on indoor environment parameters of primary school classrooms in New Zealand

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

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If you wish to print an official copy of this letter, please login to the RIMS system, and under the Reporting section, View Reports you will find a link to run the LR Report.

Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)

Human Ethics Notification - 4000021472

humanethics@massey.ac.nz <humanethics@massey.ac.nz>

Fri 2019-08-09 14:45

To: Lara Tookey <L.Tookey@massey.ac.nz>; Mikael Boulic <M.Boulic@massey.ac.nz>; Phipps, Robyn <R.A.Phipps@massey.ac.nz>; Wyatt Page <W.H.Page@massey.ac.nz>
Cc: Human Ethics <gmhumeth@massey.ac.nz>
HoU Review Group

Ethics Notification Number: 4000021472

Title: Case studies on indoor environment parameters of primary school classrooms in New Zealand

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

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If you wish to print an official copy of this letter, please login to the RIMS system, and under the Reporting section, View Reports you will find a link to run the LR Report.

Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)

Human Ethics Notification - 4000022115

humanethics@massey.ac.nz <humanethics@massey.ac.nz>

Wed 2020-02-12 18:21

To: Lara Tookey <L.Tookey@massey.ac.nz>; Mikael Boulic <M.Boulic@massey.ac.nz>; Phipps, Robyn <R.A.Phipps@massey.ac.nz>; Wyatt Page <W.H.Page@massey.ac.nz>
Cc: Human Ethics <gmhumeth@massey.ac.nz>
HoU Review Group

Ethics Notification Number: 4000022115

Title: Carbon Dioxide levels and Cognitive Performance: seeing the relationship through an electroencephalogram in Adults

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

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Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)

RE: using old data for Lara's PhD

Mikael Boulic <M.Boulic@massey.ac.nz>

Tue 2024-04-16 17:06

To: Human Ethics <gmhumeth@massey.ac.nz>

Cc: Lara Tookey <L.Tookey@massey.ac.nz>

Kia ora Patsy,

Thanks for this positive reply

Have a nice evening

Mikael

From: Human Ethics <gmhumeth@massey.ac.nz>

Sent: Tuesday, April 16, 2024 5:05 PM

To: Mikael Boulic <M.Boulic@massey.ac.nz>

Cc: Lara Tookey <L.Tookey@massey.ac.nz>

Subject: RE: using old data for Lara's PhD

Kia ora Mikael

I referred this query to one of the HEC Chairs who stated it would be acceptable for Lara to use the data given that the original consent for its use was very broad and no one will be identified.

Ngā mihi

Patsy

Patsy Broad (*she/her*) | **Team Leader**

Research Ethics Team

Graduate Research School and Ethics

Massey University | Te Kunenga ki Pūrehuroa

Private Bag 11 222, Palmerston North 4442 | New Zealand

P: DDI 06 951 6840 ext. 83840 | www.massey.ac.nz



From: Mikael Boulic <M.Boulic@massey.ac.nz>

Sent: Monday, April 15, 2024 4:10 PM

To: Patsy Broad <P.L.Broad@massey.ac.nz>

Cc: Lara Tookey <L.Tookey@massey.ac.nz>

Subject: RE: using old data for Lara's PhD

Kia ora Patsy,

No worries Patsy,

1. The 2015 low-risk application was part of course 218.340, which no longer exists. I was supervising the students, so I assisted in writing the application.
2. As you can see below, the participants agreed that data will be used for research purposes.
3. We plan to keep the anonymity of the participants. We will use the data as a cluster, so no school or teacher names will be released.

Thanks

Regards

Mikael

DOORS AND WINDOWS NEED FOR SCHOOLS

PARTICIPANT INFORMATION SHEET

My name is Francine Liaw. I am a final year student of the Bachelor of Construction, School of Engineering and Advanced Technology, Massey University, Albany. My research is entitled, "Doors and Windows Need for Schools".

Apart from being at home, children spend most of their time at school. In fact, schools are often referred to as "second homes" to children because of the amount of time they spend in school. The key objective of this study is to identify the best possible way to improve school ventilation for children, specifically with the usage of doors and windows in primary schools. The ultimate purpose for this research is to create a healthy and effective learning environment so that children can learn and study optimally.

Sampling frames for this study comprise principals, teachers and caretakers in high decile primary schools in Auckland, New Zealand. As stakeholders of high decile primary schools in Auckland, you have been invited to participate in this research survey.

I would highly appreciate it if you could grant **15 minutes** of your time to respond to the attached questionnaire.

Information collected in this project will be kept strictly confidential and used solely for research purposes. I undertake to provide you with a summary of the key findings of the study if you could complete the attached form for requesting the summary or by contacting me directly through my contact details provided below.

Participation in this research is voluntary and you are under no obligation to accept this invitation. If you do decide to participate, you have the right to:

- decline to answer any particular question;
- withdraw from the study at any time;
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when it is concluded;

Thank you very much for your time and help in my queries, please feel free to contact me through my email.

Kind Regards,

Francine Liaw

Researcher:

Francine Liaw
Email Address: francinelaw@gmail.com
Telephone: +64 (021) (082) 78746

Supervisor:

Dr. Mikael Boulic
Email Address: M.Boulic@massey.ac.nz
Telephone: +64 (09) 414 0800 ext. 84149

Disclaimer: This project has been evaluated by peer review, been reviewed by one of the University's Human Ethics Committees, and the ethical conduct of this research.

If you have any concerns about the conduct of this research, please contact Professor John O'Neill, Director of Human Ethics at Massey University.

DOORS AND WINDOWS NEED FOR SCHOOLS

PARTICIPANT CONSENT FORM - INDIVIDUAL

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature:

Date:

Full Name - printed

From: Patsy Broad <P.L.Broad@massey.ac.nz>
Sent: Friday, April 12, 2024 3:26 PM
To: Mikael Boulic <M.Boulic@massey.ac.nz>
Cc: Lara Tookey <L.Tookey@massey.ac.nz>
Subject: RE: using old data for Lara's PhD
Importance: High

Kia ora Mikael
Please accept my apologies for missing this query.

I will seek advice from one of the Ethics Chairs in regard to this, however, before I do can you please:

1. Can you please advise who submitted the low-risk notification in 2015 as I cannot find a record of the LRN by searching on your name or the course number.
2. Please clarify in both instances (2015, 2017) what participants and/or the schools consented to in terms of the storage of data and any future use of the data.

Ngā mihi
Patsy

Patsy Broad (she/her) | Team Leader

Research Ethics Team

Graduate Research School and Ethics

Massey University | Te Kunenga ki Pūrehuroa
Private Bag 11 222, Palmerston North 4442 | New Zealand
P: DDI 06 951 6840 ext. 83840 | www.massey.ac.nz



From: Mikael Boulic <M.Boulic@massey.ac.nz>

Sent: Monday, March 11, 2024 6:02 PM

To: Patsy Broad <P.L.Broad@massey.ac.nz>

Cc: Lara Tookey <L.Tookey@massey.ac.nz>

Subject: using old data for Lara's PhD

Hello Patsy,

I hope that everything is going well for you.

Part of Lara's PhD project is to investigate "teachers opening windows/doors to refresh NZ classrooms".

In 2015, I supervised two bachelor students who deployed a questionnaire in 40 Auckland schools (Low-risk application as part of Course 218.340).

In 2017, I supervised another research team (Lara was part of the team) that deployed the same questionnaire in 17 Christchurch and Dunedin schools (Low-risk application #17712).

As part of her PhD, Lara would like to compare the change pre-COVID/post-COVID in opening windows in NZ schools by using the old data and comparing it to her own data.

We asked both 2015 students and they are happy for Lara to use their data for further analysis.

We are not focusing on a particular teacher (analysis of data will be at a cluster level). The school or teacher won't be identified. Everything is anonymized.

Would Lara be able to use the 2015 data and her collected 2017 data as part of her current PhD project?

Thanks

Best,

Mikael

SOA 21/53 Carbon Dioxide and thermal comfort in the classroom: The impact on student's cognitive performance (8-12 year old students)

Mrs Lara Tookey (HEC: Southern A Application SOA 21/53)

Department: School of Built Engineering

Supervisor: Dr Mikael Boulic; A/Prof Wyatt Page; Dr Hennie van Heerden; Dr Barry McDonald

The application was provisionally approved, subject to the fulfilment of the conditions below to the satisfaction of Dr Negar Partow (Chair).

Please note that the Committee is always willing to enter into dialogue with applicants over the points made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

Dear Dr Negar Partow, in response to our conversations on Friday 10th December 2021, and again on Monday 14th February 2022, please find my comments below in green for clarity.

- Given current Alert Level restrictions, please outline the plan in place to ensure research is conducted in a safe manner. Note: The research should be consistent with national COVID regulations (<https://covid19.govt.nz/>) and current Massey University guidelines. For supervisor's: Refer to guidance in the Massey University Pandemic Plan (<https://masseyuni.sharepoint.com/sites/Coronavirus>). For student's: Refer to https://www.massey.ac.nz/massey/about-massey/news/advice-on-coronavirus-outbreak/advice-on-coronavirus-outbreak_home.cfm I will comply with both Massey University, Government and Ministry of Education guidelines when conducting field research and observation studies.
- If the researcher wants to use passive consent from parents (opt-out), there is an obligation for parents to receive notification regarding the research directly, e.g., by email, paper copy or other means, rather than via the school newsletter (which might not be read). Please refer to the National Ethics Advisory Committee (NEAC) National Ethical Standards, Chapter 7, Informed Consent: National Ethical Standards. I have asked the Principals of the schools that have already indicated they wish to participate, and they have agreed to post the Information sheets to the Parents/Caregiver. They will also post reminders. I will reimburse the schools for the cost of postage.

In addition, I am creating a website about the research, which parents will be able to access – eMascot@weebly.com

Parents will be updated via the website directly when I start to publish the outcomes.

- Do schools receive any form of koha for participation? The committee noted there is a lot of work involved for them. Yes, I will be giving each school that participates a \$150.00 voucher to purchase books for their school library. This information has been added to the Information Sheet for the Parents/Caregivers.

PROJECT SUMMARY

Q6, page 3

- Paragraph two, final sentence should read "...where they spend their day *fall outside* these recommendation levels" (not fall out with). – *duly noted and amended*

PEER REVIEW

Q7, page 3

- Point 4 notes four tests have been selected; however, the CANTAB questionnaire has up to 8 tasks. Is this a modified CANTAB? If so, please state this. – *this study only has 4 tasks. However, if the students wish to refresh their memory they can voluntarily opt to do a tutorial of each task prior to undertaking the quiz tasks, this will increase the number of tasks available (to a total of eight).*

ETHICAL ISSUES CONSIDERED

Q8, page 3

- The third paragraph states parents will be given three weeks' notice, with a reminder. However, elsewhere, two weeks' notice is referenced. Please ensure consistency. – *duly noted and amended and two weeks*

SECTION B

B3

- The response states "Once the Principal has consent to the research, the Year 4-6 teachers have been co-opted into the study". However, participation is voluntary for all research participants and therefore, teachers must be given time to consider whether they wish to take part, or not. Please consider and comment. *Consent will initially be sought from the Principal. Once that has been obtained, the researcher will host a tea for all the Year 4-6 teachers (and any others that are interested) and outline the research study. The website, and a short video will also be made available which teachers can view at their own time. After participating in the tea and/or viewing the website & video, they then decide whether they wish to participate or not.*
- Teacher participation is not compulsory, no is no coercion.
- Might the teachers feel obliged to participate if the Principal is keen for the study to take part in their school? *We have been working with a number of schools for the past several years, so both the Principals and Teachers from Years 1-6 are already actively engaged in the Healthy Schools project and have expressed interest in participating in my research project. However, I do respect the fact that it is essential that the research cannot be conducted without the participation of the Teachers, so unless the Teacher is fully onboard, then no, their classroom is not included. Access is also negotiated with each teacher to fit within their study plan.*
- Might parents also feel obliged for fear of adverse educational consequences for their children? Please consider and comment. *All testing is at a classroom level and does not individually impact success of student attainment, therefore negative consequences are not anticipated. The idea of the research is to improve educational facility operational protocols.*

SECTION C

C2

- The response states the ideal sample size is 384 range of classrooms.. Please clarify where this number comes from. Note: The researcher is analysing the data at classroom level. Wouldn't the number of classrooms be more important than the number of students?
- The Ministry of Education does not keep records on the number of 'Year' classes, but it does keep records of students enrolled per 'Year'. In 2021 there were 65092; 65832; and 66165 students enrolled in 'Year 4'; 'Year 5' and in 'Year 6' respectively. Assuming an average class size of 30 students, and a 6% sample size, we would sample 384 classrooms. The 6% is a result of COVID-19 and financial restrictions.

C4

- If the parent does not give non-consent (i.e., passively opts in), will the child be able to opt-out themselves? What happens if the child opts-in and the parent opts-out? What would be the impact to the child of differing options? Massey Code of Ethical Conduct pg5 'Child participants can provide consent if the researcher applied from around the age of seven, but it can be younger.' It would obviously be best if both parents/caregivers and the child were both in agreement. I would recommend that they sit down and discuss this openly and try and find out why one party say Yes and the other No. If they are still not able to agree, I would offer to meet with the parents.

SECTION F

F6

- Not all children in New Zealand who need a teaching assistant get one and there may be other children with educational needs without a teaching assistant. How will these children be helped to understand the study and provide informed consent? Teachers, classroom teacher aids, and I will be on hand to answer any questions the students may have. Furthermore, a one-minute video will be made showing similar aged students undertaking the CANTAB tests. A similar method was used by a colleague in her PhD (HEC Southern A Application 12/49) which was well received by both Principals and Teachers.

SECTION G

G3/G6

- What if the conditions mean that the teacher needs to open/close windows due to the weather and yet this is not the day for this activity? For example, what if the teacher is supposed to be keeping the windows/doors closed and yet the weather is very hot, or is supposed to be keeping them open yet the weather is very cold? Using the CO2 / thermal data already collected, we will be able to predict the behavior within the classrooms. Working with NIWA (weather patterns) to ensure we exclude extreme outliers, we should be able to avoid this situation from occurring. Should this however be the situation, we will reverse the protocol. If not, we abort the measurements and try again another time.
- Please also refer to minor amendment
- If heating/cooling options are available in the classroom (and routinely used), will staff be able to use these as usual? Yes, this information will be noted.

SECTION L

L9

- Is there a reason for keeping the data this long? The researcher is doing their PhD part-time.

SECTION P

P1

- Bullet 5 – is discussion on wearing bicycle helmets and concussion in school sport outside the scope of this study? This has been removed

P2

- Some children can become very stressed by tests or the results of them. Will participants get the results, and might this stress some if they get what they perceive to be a poor score? No, no student will receive any data or feedback on any of the CANTAB tests. All results of the testing phase will be presented as an amalgamated classroom result. Neither the researcher, teacher nor Principal will receive any data on individual student scores since it is irrelevant to the thesis of the study. Student information will be recorded so no student results will be available. Only class A, class B etc.

P6

- Where the child and/or parent says ‘No’ what happens to the child during the study period. Are they outside the classroom? As it takes place over the whole day, does the child leave the room or do they have to sit there and take part passively anyway? The test takes place for 10 minutes, four times a day. No student will need to leave the classroom. The students who are not participating will be given a short reading or some other activity set by the teacher to complete while the remainder of the class does the CANTAB test.
- Please refer to minor amendment

INFORMATION SHEET FOR PARENTS/CAREGIVERS

- “All year 4 - 6 classrooms in your child's school have been selected as part of the study.” This suggests that teachers do not have a choice as to whether they take part, or not. Is that the case? No, the researcher will first obtain the Principal consent, then advise the Year 4-6 teachers of the study. They will then have the option to participate or not.
- Include statement that opting out of the study will not affect your child’s education. – duly noted and amended
- Clarify what will happen if the child has a differing opinion to the parent/caregiver about taking part in the research. – duly noted and amended

INFORMATION SHEET FOR TEACHERS

- “Lara will donate her time during the research.” What does this mean? What specific tasks will she donate her time for? – duly noted and amended
- Make clear teachers should speak to children so they understand the test is not about them. – duly noted and to be included in the briefing

INFORMATION SHEET FOR CHILDREN

- Ensure the information sheet is proof-read to eliminate errors and that it is age appropriate, user-friendly language. Note: Suggest a primary school teacher proofreads the information sheet and questionnaire for children to check comprehension for children 8-10 years. – *duly noted. A teacher and appropriately aged child have proof read the documents.*
- Clarify what will happen if the child and parent/caregiver have differing opinions. – *duly noted and included*
- “This paper talks about” – rephrase e.g. “This handout...” – *duly noted and amended*

ALL INFORMATION SHEETS

- Please include the correct committee approval statement, as follows: *This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 21/53. If you have any concerns about the conduct of this research, please contact Dr Negar Partow, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63363, email humanethicsoutha@massey.ac.nz.* – *duly noted and amended*
- Please upload amended information sheets.

IMPACT OF CLASSROOM ENVIRONMENT QUESTIONNAIRE

- “I went to *bed* late” (not be). – *duly noted and amended*
- “Select the answer which *suits* how you feel” (not *suites*), although this language may not be suitable for children - perhaps use “describes”. – *duly noted and amended*
- Upload amended questionnaire.

SOA 21/53 Carbon Dioxide and thermal comfort in the classroom: The impact on student's cognitive performance (8-12 year old students)

Mrs Lara Tookey (HEC: Southern A Application SOA 21/53)

Department: School of Built Engineering

Supervisor: Dr Mikael Boulic; A/Prof Wyatt Page; Dr Hennie van Heerden; Dr Barry McDonald

The original application was provisionally approved, subject to the fulfilment of the conditions below to the satisfaction of Dr Negar Partow (Chair).

Dear Dr Negar Partow, in response to our conversation on Monday 14th February 2022, below please find my application for minor amendments to the above application.

Initial Assessment

Project detail - 6 Project Summary:

Under the COVID-19 pandemic, NZ MOE has decided to strengthen the DQLS criteria (an increase of ventilation rate) to reduce SARS-CoV-2 transmission rates in classrooms. As a result, the CO₂ maximum threshold has been decreased from 1200 ppm to 800 ppm. The Ministry of Education has advised all schools that windows should remain open at all times (9 am – 3 pm). This action may be appropriate for the summer seasons; however, significant heating will be required during winter seasons to keep the classroom at a comfortable level.

As such, I can no longer conduct the intervention study Day 1/Day 2. Instead, it will occur once a week, embedded into the teaching program as desired by the teacher.

Full Application Details

B 2 Background of the project.

Paragraph 2 - Ministry of Education has decreased the CO₂ threshold from 1200 ppm to 800 ppm.

B 3 Outline research/teaching/evaluation procedures including approach/procedures for collecting data and analysis.

Classroom setting:

~~During the two-day event, the teacher will perform their duties as usual. On day one, the PI will record how they manage the classroom environment (doors/windows open or closed) & on day two, the PI will reverse this natural setting. If windows were open on day one, they would be closed on day two.~~ This section is no longer valid as no intervention study will be conducted. Furthermore, the PI is not permitted into the classroom during the red and orange traffic light. So, after discussions with the supervisory team, it was decided to create visual instruction material for the teachers/students. We have also decided to only include Y5 and Y6 due to their ability to follow instructions quickly.

The PI will meet with each consenting teacher. They will each select a suitable 20 minute period for their student group. The time should remain the same for the first term, but it could change next term.

Observation time off tasks:

This can only be carried out under the green traffic light.

Sensory questionnaire:

This will be conducted each week.

B 5 Describe the location/setting in which you will collect data? *

The PI has 1.5 years in which to collect data. Under the current COVID-19 conditions, it is unlikely that the PI will be able to continue her teaching commitments at Massey University and reestablish relationships with schools at Hawkes Bay, Palmerston North, Wellington, Christchurch and Dunedin. The PI's supervisors have suggested that the focus remains in Auckland.

C. Participants**C 1 How many participants will be involved? ***

We anticipate the involvement of between 2 – 10 primary schools (Year 5 - Year 6 classes) ~~with an expected involvement of between 200 – 500 student participants.~~ Student numbers are not a concern in this research as only classroom numbers are being reported.

C 2 Provide the reason for selecting this number or the statistical justification (if relevant).

The justification is given from similar research studies.

Regards

Lara

IMPACT OF INDOOR AIR QUALITY ON COGNITIVE PERFORMANCE IN YOUR SCHOOL

Information Sheet for School Principal and Teachers

When is the study going to take place?

We will be asking the school to participate from September 2022 until the end of 2022. If you are willing to repeat the cycle, from Feb 2023 till June and then perhaps again for the remainder of the 2023 year.

What do I have to do to participate?

There are two stages to the research. Both will be explained in full when we come to your school.

Stage 1: Classroom Indoor air quality and windows monitoring

- a) The Principal Researcher (PR) will install one indoor air quality monitoring device (similar to the CO2 sensor supplied by MOE) that will monitor the CO2, temperature and humidity inside the classrooms.
- b) The PR will also install window/door sensors to monitor the opening and closing patterns of windows/doors in classrooms during the summer/winter periods. Not all classrooms will have sensors installed, so the PR will record weekly the remaining classrooms.

Stage 2: Cognitive performance test

The PR will arrange a suitable date with each teacher from year 5 and 6 classes to embed a 20 minute session per term cognitive test throughout Term 3 and Term 4 into the curriculum.

If you are interested in having your school participate in this research, please complete the consent form. If you do not wish to participate, please put a line through the consent form.

If you agree to participate in the research, you are free to withdraw until the start of data analysis. We guarantee that all the information we gather from this project will be kept confidential. We will never present individual results that identify you as a principal, the teachers or the children. The names of the schools involved in the study will be anonymised. The research findings are based at the classroom level, not an individual level.

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 21/53. If you have any concerns about the conduct of this research, please contact Dr Negar Partow, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63363, email humanethicsoutha@massey.ac.nz.

If at any stage you would like to discuss any part of this research or your participation in it, please phone the study principal researcher Lara Tookey (027 537 2099) or Dr Mikael Boulic, Lara's PhD supervisor, (09 213 6546). You can also email Lara at l.tookey@massey.ac.nz or Mikael at m.boulic@massey.ac.nz.

With thanks
Lara Tookey

IMPACT OF INDOOR AIR QUALITY ON COGNITIVE PERFORMANCE IN YOUR SCHOOL

PRIMARY SCHOOL CONSENT FORM - PRINCIPAL

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

Please tick the box only if you agree with the proposition:

- ☐ *I agree* to the installation and ongoing monitoring of indoor air quality in selected classrooms.
- ☐ *I agree* that Lara Tookey/Mikael Boulic may observe the school buildings to record “windows open” for the duration of the study, respecting School policy and COVID-19 restrictions.
- ☐ *I agree* to participate in this study under the conditions set out in the Information Sheet.

Signature:

Date:

Full Name - printed

IMPACT OF INDOOR AIR QUALITY ON COGNITIVE PERFORMANCE IN YOUR SCHOOL

PRIMARY SCHOOL CONSENT FORM - TEACHER

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

Please tick the box only if you agree with the proposition:

☐ *I agree* to participate in this study under the conditions set out in the Information Sheet.

Signature:

Date:

Full Name - printed

IMPACT OF INDOOR AIR QUALITY ON COGNITIVE PERFORMANCE AT YOUR CHILD'S SCHOOL

Information Sheet for Parents/Caregivers

Kia ora, I am Lara Tookey, a Senior Tutor at Massey University. I am doing a research study on the impact of classroom indoor air quality on student concentration and memory (cognitive performance) in New Zealand primary schools.

All year 5 - 6 classrooms in your child's school have been selected as part of the study. There has been very little research done on indoor air quality in primary schools in New Zealand. I plan to conduct a research project investigating the impact of the natural classroom environment on your child's cognitive performance.

As you may be aware, the Ministry of Education (MoE) requires schools to keep windows open at all times to ensure maximum ventilation. This is to minimise the impact of COVID-19 transmission and to ensure minimal carbon dioxide (CO₂) build-up. The MoE aims to keep CO₂ at 800 ppm (parts per million). Prior to COVID-19, CO₂ levels of 1200 – 1500 ppm was acceptable. 800 ppm may be achievable in the warmer seasons when keeping windows open is feasible, but what will happen in winter, when the classrooms need to be kept warm.

Your child will be asked to complete an online cognitive test once per week (10 min/test). Your child is familiar with working in an online environment since the COVID19 lockdowns in 2020 & 2021. The test is no different from the STAR reading & PAT maths tests they do regularly. In fact, the cognitive test is more like a computer game and only takes 10 minutes.

Your child will also be asked to answer two sensory questions each day. How energetic they felt and how hot/cold they felt. They will also be asked if wearing a mask makes their head hurt.

When is the study going to take place?

We will be asking the school to participate from late August/September 2022.

What do you have to do to participate?

- NOTHING.
- You have been given an opt-out form. If you prefer that your Child **DOES NOT** participate in the research, complete the form and return it within two weeks of the notice date.

There is no financial cost to you for any part of this project. However, the school will receive a \$150 voucher for purchasing books for their school library.

If you agree to allow your child to participate in the research, you are free to withdraw your child until the start of data analysis. We guarantee that all the information we gather from this project will be confidential. We will never present individual results that identify you, your child, or your school. The research findings are based at the classroom level, not your child's level.

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 21/53. If you have any concerns about the conduct of this research, please contact Dr Negar Partow, Chair, Massey University Human Ethics Committee: Southern A, telephone 04 801 5799 x 63363, email humanethicsoutha@massey.ac.nz.



If you would like to discuss any part of this research or your participation, please phone the principal investigator, Lara Tookey (027 537 2099) or Dr Mikael Boulic (09 213 6546). You can also email Lara at l.tookey@massey.ac.nz or Mikael at m.boulic@massey.ac.nz.

Frequently Asked Questions and Answers

Q: Will any artificial stimulants be added to the classroom? A: No artificial stimulants will be added to your child's classroom. The only change to the environment will be the opening and closing of doors and windows.

Q: How will your child's concentration and memory be assessed? A: This will be done with computer software, designed by a company in England, Cambridge Brain Sciences, which has been validated by more than 25 years of research and over 300 peer-reviewed studies.

Q: How difficult will it be for my child to do the test? A: Your child already does online work endorsed by the Ministry of Education. This test, which is more like a game, will only take 10 minutes.

Q: What will your child do if they do not participate in the study? A: They will do a quiet activity set by the teacher for 10 minutes.

IMPACT OF INDOOR AIR QUALITY ON COGNITIVE PERFORMANCE

OPT-OUT (PASSIVE) CONSENT – PARENT/CAREGIVER

I have read the Information Sheet, and I DO NOT wish my child to participate in the classroom cognitive performance tests. After reviewing the material, I do not want

(please print student's name)

to participate in the “Impact of Indoor Air Quality on Cognitive Performance” research project, even though the data collected will only be analysed at a classroom level, not at an individual student level.

I understand that she/he will remain in the class and perform some other classroom activity during the time the cognitive test is being administered.

Signature: _____ Date: _____

Full Name of
Parent/Caregiver
(Please print) _____

Reason(s) for not
participating _____

Informed Assent Form



What is a research study?

Research studies help us learn new things. We can test new ideas. First, we ask a question. Then we try to find the answer.

This handout talks about our research and the choice that you have to take part in it. I want you to ask me any questions that you have. You can ask questions any time.

Important things for you to know...

- You get to decide if you want to take part.
- You can say 'No' or you can say 'Yes'.
- No one will be upset if you say 'No'.
- If you say 'Yes', you can always say 'No' later.
- You can say 'No' at anytime.



Why am I doing this research?

I am doing this research to find out more about how your classroom indoor air quality impacts on how you concentrate and remember things.



What would happen if I join this research?

If you decide to be part of this research, I would ask you do do two things:

- Take a quiz on the computer that looks like a computer game twice a term.
- Answer some questions. The first question is about how sleepy you feel and why. The next question is about how hot or cold you are feeling. The final question is about your face mask and if it makes it difficult to breath.



Could bad things happen if I join this research?

NO! The quiz that you will do is not the same as any of your other tests. There will be no record kept of your grade. Also, you will get to practice (as many times as you wish) before you do it. So there will be no reason to be scared of doing it.



Could the research help me?

Yes, it could. However we may find that your teacher already keeps the classroom well ventilated. But what happens when the weather gets cold, and the windows are closed? How do we keep the air fresh then?



What else should I know about this research?

What if I want to be part, but my parents/caregivers say no. Well, then it would be a good idea to sit down as a family and talk about why you have different ideas. Be honest with each other. But, please know you do have the right to be part of the study according to Massey University Code of Ethics. I am happy to speak to them.

If you do not want to be in the study, you do not have to be. You will do a reading exercise when your friends do the online quiz.

It is also OK to say yes and then change your mind later. You can stop being in the research at any time. If you want to stop, you just need to tell me.

You can ask questions any time. Ask any questions you have. You can talk to me, Lara when I am in your class, or you can phone me on 027 537 2099, or you can email me on l.tookey@massey.ac.nz



If you want to be in the research

Please write your name below. I will write my name too. This shows we talked about the research and that you want to take part.

Name of Participant

(To be written by child)

Printed name of
Researcher

Signature of Researcher

Date

Time

Copies to: Parents/Caregivers

Appendix D

New Zealand

D.1 The NZ context

Seasonal periods in the southern hemisphere

In NZ, a southern hemisphere country, the seasons are:

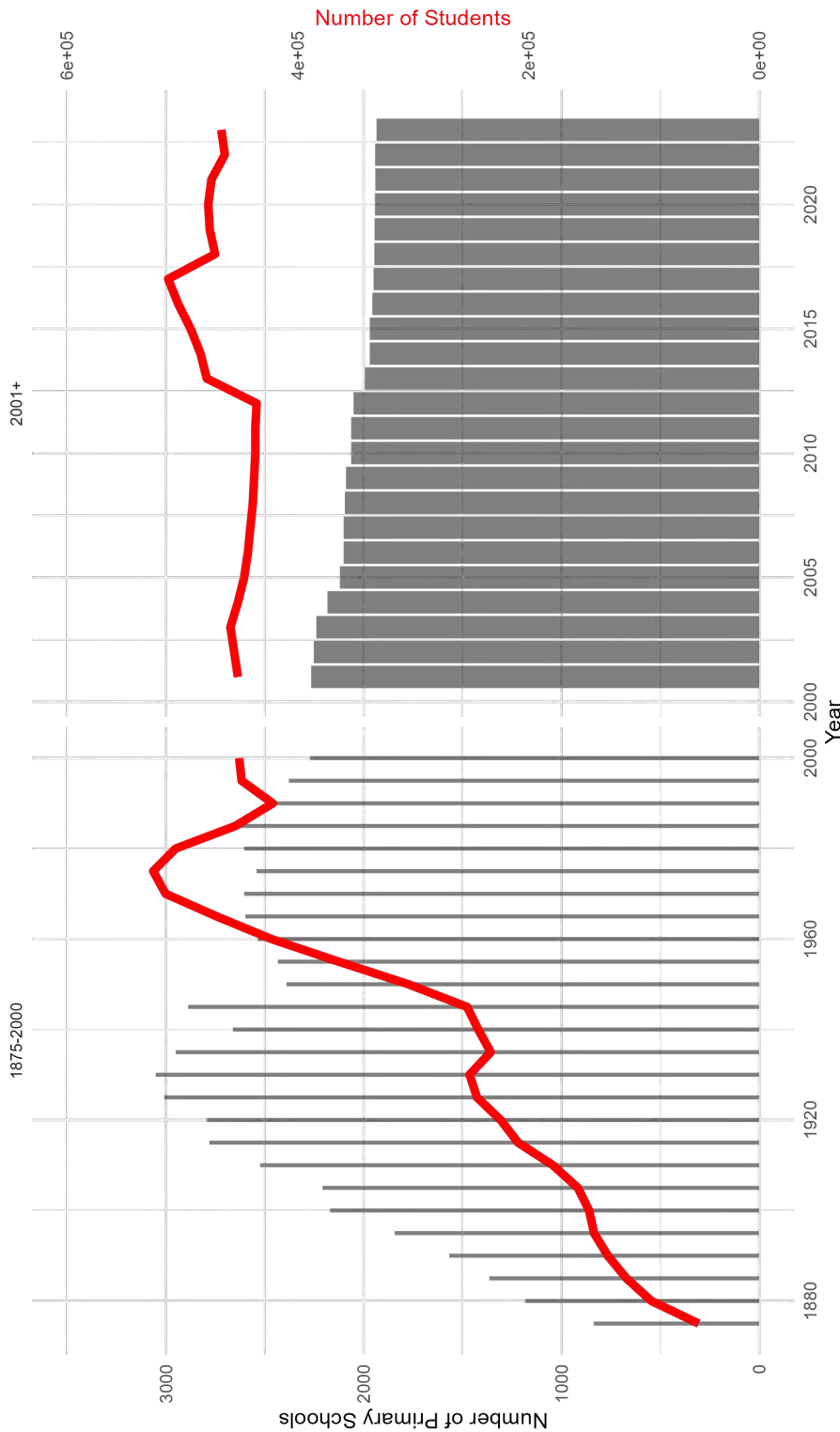
- Spring seasons cover September, October and November;
- Summer seasons cover December, January and February;
- Autumn seasons cover March, April and May, and
- Winter seasons cover June, July and August.

D.1.1 Number of primary schools and ages thereof

In NZ, primary education comprises all primary schools serving students aged 5 to 13 (Years 1 to 8), primary schools for ages 5 to 10 (Years 1 to 6), and intermediate schools for students aged 11 to 13 (Years 7 and 8) (Ministry of Education, 2023). **Figure D.1** displays historical primary school counts and student enrolments from Year 1 to Year 8 between 1875 and 2023. The data collection frequency shifted from a 5-year interval before 2000 to annual updates after that. They were analysing 30-year intervals from 1875 to 2023 (as shown in **Figure D.2**). The number of schools in NZ experienced fluctuating trends, indicating periods of growth and decline driven by various factors, including socioeconomic changes and educational policies. In June 2023, there were 1,935 primary schools, reflecting a downward trend in school numbers over time (Teaching Council of Aotearoa New Zealand, 2023).

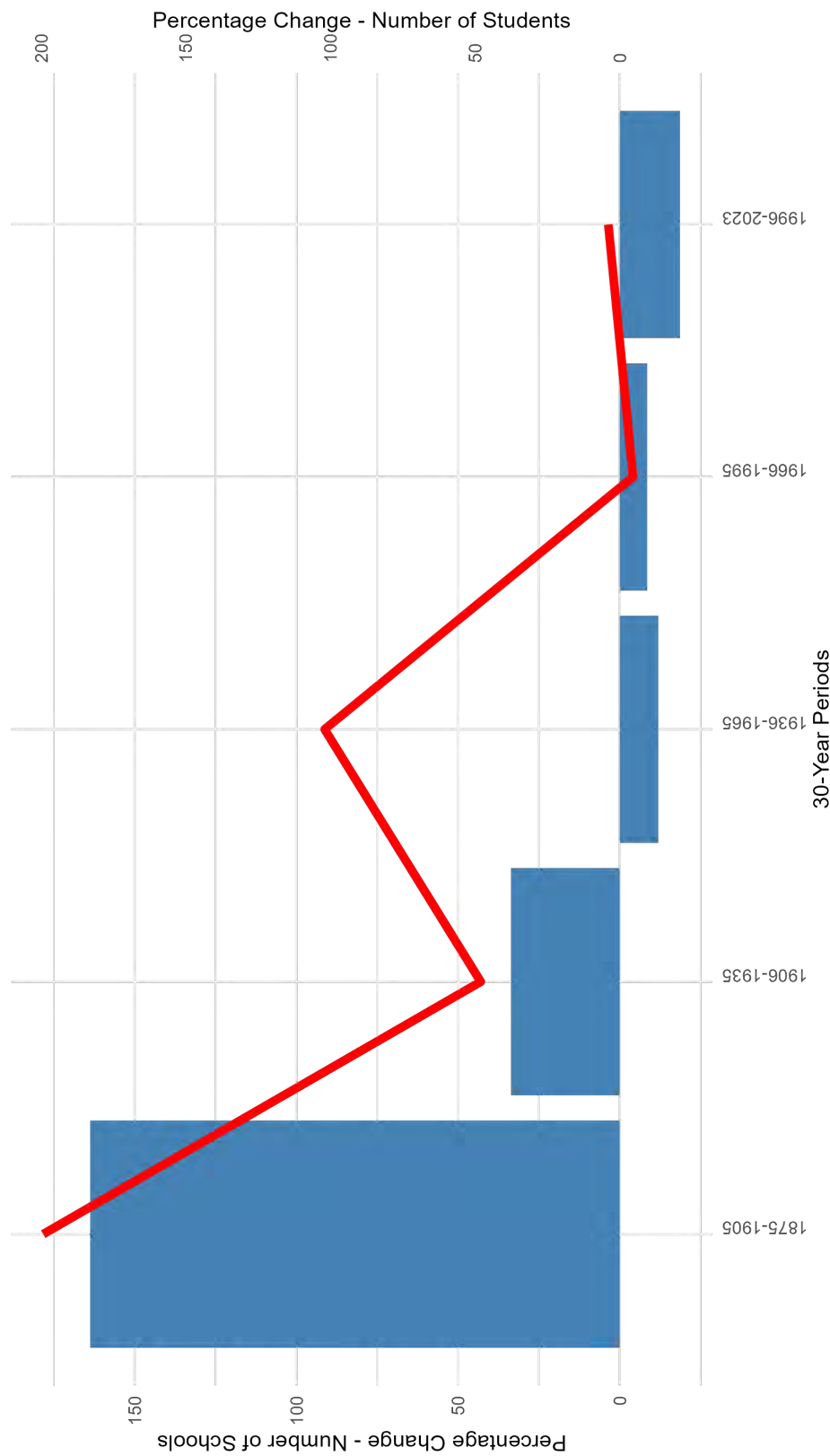
Over three decades, from 1875 to 2023, the number of students in NZ (**Figure D.2**) exhibited variable growth rates. There was a remarkable 199.32% surge in students from 1875 to 1905, followed by a more moderate 48.05% increase leading up to 1935. Subsequently, from 1936 to 1965, there was a substantial increase of 102%, which then reversed with a decrease of 4.59% from 1966 to 1995. The most recent period from 1996 to 2023 showed a slight 3.93% increase, suggesting a stabilisation in student population growth and reflecting the dynamic changes in NZ's educational landscape over the last century.

FIGURE D.1: Number of NZ Primary Schools and Students from 1875 to 2023



Source: Authors Own

FIGURE D.2: *Percentage Change in Number of Schools and Students over 30-Year Periods 1875-2023*



Source: Authors Own

The fluctuating number of schools in NZ over the years can be mainly attributed to shifts in student population demographics. The significant increase in student numbers from 1875 to 1905 required increased school construction to accommodate the growing youth population. This trend continued with a more moderate increase up to 1935, likely influenced by ongoing demographic changes and urbanisation.

The historical evolution of NZ's educational infrastructure reflects various factors such as student demographics, economic circumstances, policy changes, and evolving pedagogical practices. Understanding these influences is crucial for informing future educational strategies that align with the changing needs of the academic community.

This overview traces the historical trends in NZ's primary education system from 1875 to 2023, emphasising the fluctuations in school numbers and student populations while exploring the demographic, economic, and policy factors that have shaped the educational landscape. Reviewing the history and composition of Crown school property is essential to fully grasp the current state and challenges of educational infrastructure in NZ.

D.1.2 Crown school property

As of 30 June 2023, NZ's state school property portfolio comprised more than 2,538 schools, including those on Stewart Island, Chatham Island, Pitt Island and Waiheke Island (Ministry of Education, 2023). The NZ School Property Strategy 2011-2021 indicates that nearly 70% of school buildings are between 30 and 100 years old, with around 5,500 being re-locatable structures initially brought onto school sites for temporary capacity needs (Ministry of Education, 2023).

The school property can be categorized into four distinct phases:

1. **Before 1950:** Traditional classroom structures were predominant.
2. **1950 - 1980:** The Ministry of Works era saw the construction of standardised school blocks in response to post-World War II educational demands, with robust timber construction lacking modern efficiency standards (Browne and Sameshima, 2012).

3. **1980 - 1990:** Prefabricated structures with lightweight timber frames were introduced to accommodate demographic shifts, often leading to suboptimal acoustic conditions due to construction details (Browne and Sameshima, 2012).
4. **Post-1990s:** A move toward decentralised property management brought various school buildings, including custom-designed structures, to support evolving educational methodologies. Recent trends favour open-plan teaching spaces for flexible learning environments, with newer structures featuring improved thermal insulation but facing challenges with overheating due to extensive glazing.

Most of NZ's primary school buildings, erected between 1950 and 1980, follow conventional designs such as Nelson, Avalon, Dominion, Canterbury, and Formula block layouts. For more information on the various school typologies, please refer to [Catalogue of Standard School Building Types](#).

Examples of NZ Classroom Construction

The NZ classroom construction examples presented in this thesis are essential for contextual relevance to the geographical area under study, aiding in comparative analyses of IEQ across different construction methods. These examples offer practical insight into applying IEQ principles within real-world settings, aligning research outcomes with NZ's specific building practices and regulations. The thesis improves empirical rigour by showcasing diverse classroom designs, highlighting specific IEQ challenges and opportunities within the NZ context.

Starting with the historic Skippers community school building (**Figures D.3 and D.4**) and progressing to the modernised Freemans Bay School (**Figures D.5 and D.6**), these examples illustrate the evolution of classroom construction in NZ over time.

FIGURE D.3: *Upper Shotover Public School External*



Source:

<https://www.flickr.com/photos/volvob12b/25813363890>

FIGURE D.4: *Upper Shotover Public School Internal*



Source:

<https://www.heritage.org.nz/list-details/5176/Skippers>

FIGURE D.5: *Freemans Bay Blue Zone*

Source:

<https://www.archdaily.com/922566/freemans-bay-school-rta-studio>

FIGURE D.6: *Freemans Bay Internal Zone*

Source:

<https://www.archdaily.com/922566/freemans-bay-school-rta-studio>

The Blackwater School (**Figures D.7 and D.8**) and the Cambridge Primary School (**Figures D.9 and D.10**) transformations further emphasize the adaptation of educational spaces to meet changing needs and standards. These illustrations bridge theoretical frameworks with tangible educational construction elements, aiming to influence building standards and enhance indoor environments for educational settings.

FIGURE D.7: *Blackwater Public School External*



Source:

<https://blackwaterschool.co.nz/>

FIGURE D.8: *Blackwater Public School Internal*

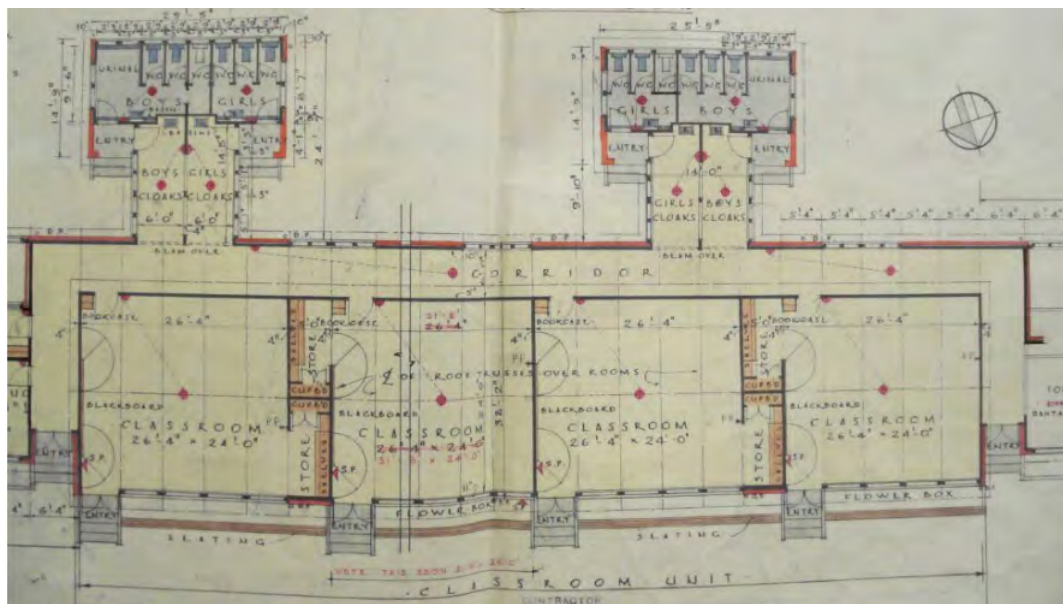
Source:

<https://blackwaterschool.co.nz/>FIGURE D.9: *Cambridge Primary School*

Source:

<https://www.heritage.org.nz/list-details/4157/Listing>

FIGURE D.10: Basic Four Room Unit of Dominion Basic Plan



Source:

Department of Education, ANZC, CH564, box 177, RS/181

Selection of school weeks for Hawke's Bay, Christchurch, and Dunedin 2017 to 2018 study

TABLE D.1: *Selected School Weeks by Season and Region for the Study*

Season	Region	Typical term start date (Mon)	Typical term end date (Fri)
Spring	Hawke's Bay	20 Nov	24 Nov 2017
	Christchurch	6 Nov	10 Nov 2017
	Dunedin	6 Nov	10 Nov 2017
Summer	Hawke's Bay	12 Feb	16 Feb 2018
	Christchurch	12 Feb	16 Feb 2018
	Dunedin	27 Nov	1 Dec 2017
Autumn	Hawke's Bay	19 Mar	23 Mar 2018
	Christchurch	5 Mar	9 Mar 2018
	Dunedin	5 Mar	9 Mar 2018
Winter	Hawke's Bay	4 Jun	8 Jun 2018
	Christchurch	2 Jul	6 Jul 2018
	Dunedin	20 Aug	24 Aug 2018

School term weeks for the Auckland study 2022 to 2024

TABLE D.2: *Term Weeks for Auckland Study*

Term	Typical start date	Typical end date	Season
3	25/07/2022*	30/09/2022	Winter and Spring
4	17/10/2022	20/12/2022	Spring and Summer
1	30/01/2023	06/04/2023	Summer and Autumn
2	24/04/2023	30/06/2023	Autumn and Winter
3	17/07/2023	22/09/2023	Winter and Spring
4	09/10/2023	13/12/2023	Spring and Summer
1	01/02/2024	12/04/2024	Summer and Autumn
2	29/04/2024	05/07/2024**	Autumn and Winter

* Study began on 29/08/2022

** Study concluded on 21/06/2024

TABLE D.3: *School Weeks - Term One, 2023*

Week No.	Start date	End date	RM5	RM6	RM7
1	3/1	3/2	Yes	No	No
2	7/2	10/2	Yes	No	No
3	13/2	17/2	Yes	No	No
4	20/2	24/2	Yes	No	No
5	27/2	3/3	Yes	No	No
6	6/3	10/3	Yes	No	No
7	13/3	17/3	Yes	No	No
8	20/3	24/3	Yes	No	No
9	27/3	31/3	Yes	No	No
10	3/4	6/4	Yes	No	No

TABLE D.4: *School Weeks - Term Two, 2023*

Week No.	Start date	End date	RM5	RM6	RM7
1	24/4	28/4	No	No	No
2	1/5	5/5	No	No	No
3	8/5	12/5	No	No	No
4	15/5	19/5	No	No	No
5	22/5	26/5	Yes	No	No
6	29/5	2/6	Yes	No	No
7	5/6	9/6	Yes		
8	12/6	16/9	Yes		
9	19/6	23/9	Yes		
10	26/6	30/6	Yes		

TABLE D.5: *School Weeks - Term One, 2024*

Week No.	Start date	End date	RM5	RM6	RM7
1	1/2	2/2	No	No	No
2	5/2	9/2	No	No	No
3	12/2	16/2	No	No	No
4	19/2	23/2	No	No	No
5	26/2	1/3	Yes	No	Yes
6	4/3	8/3	Yes	No	Yes
7	11/3	15/3	Yes	No	Yes
8	18/3	22/3	Yes	Yes	Yes
9	25/3	29/3	Yes	Yes	Yes
10	1/4	5/4	Yes	Yes	Yes
11	8/4	12/4	Yes	Yes	Yes

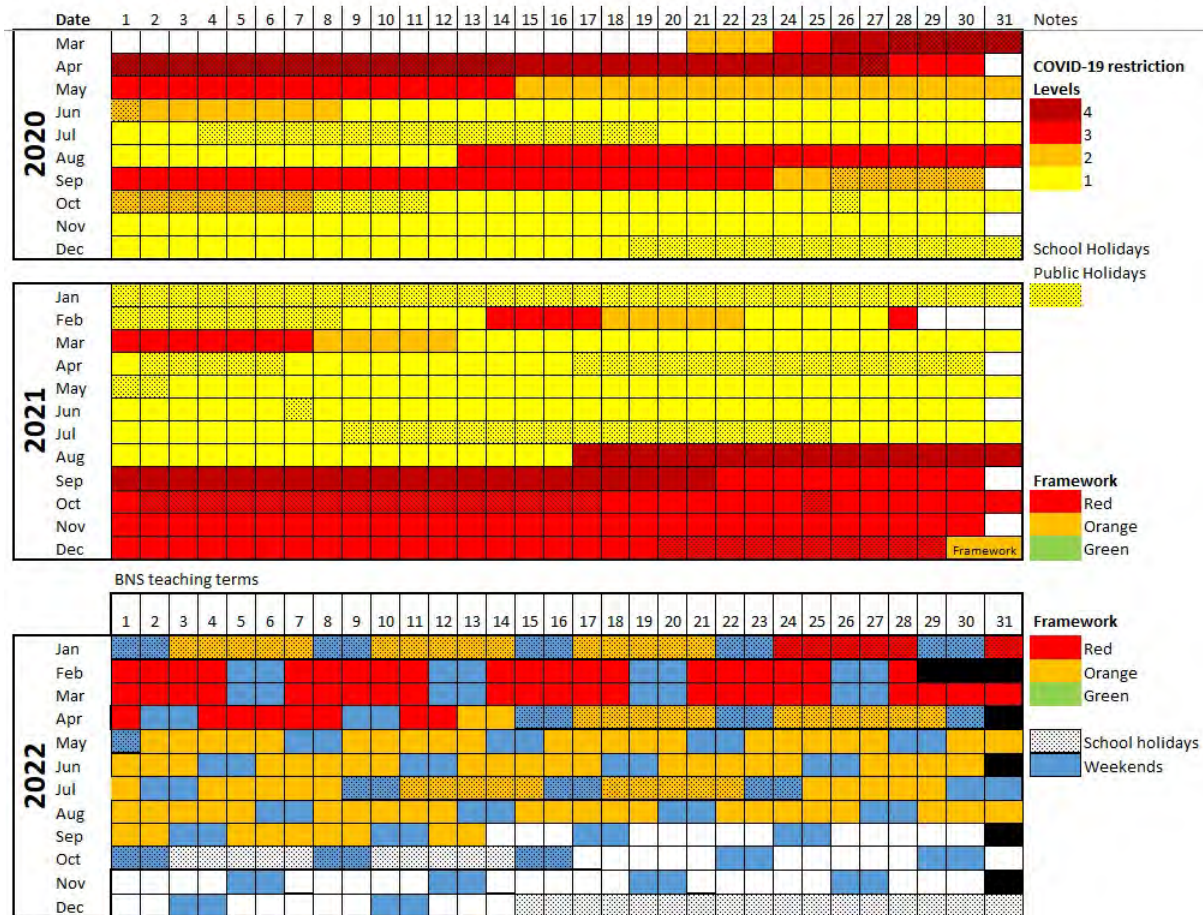
TABLE D.6: *School Weeks - Term Two, 2024*

Week No.	Start date	End date	RM5	RM6	RM7
1	29/4	3/5	Yes	Yes	Yes
2	6/5	10/5	Yes	Yes	Yes
3	13/5	17/5	Yes	Yes	Yes
4	20/5	24/5	Yes	Yes	Yes
5	27/5	31/5	Yes	Yes	Yes
6	3/6	7/6	Yes	Yes	Yes
7	10/6	14/6	Yes	Yes	No
8	17/6	21/6	Yes	No	No

No data collected after this date

Figure D.11 outlines the various COVID-19 conditions that impacted the first three years of the doctoral study.

FIGURE D.11: *Impact of COVID-19 on Part-time Doctoral Studies*



As is evident from **Figure D.11** from February 2020 to December 2022, NZ's response to COVID-19 involved a series of Alert Level changes, directly impacting school closures across the country, with Auckland experiencing some of the most stringent and prolonged restrictions.

- **February - March 2020:** As the first cases of COVID-19 emerged, schools across Auckland, like the rest of NZ, were closed when the nation moved to Alert Level 4 on 25 March 2020.
- **Early 2020:** Following the initial outbreak, non-essential domestic travel was limited, particularly during national and regional lockdown phases (e.g., Alert

Level 4 in March 2020). As NZ moved to lower alert levels, domestic travel options expanded but were subject to regional restrictions, particularly if certain areas were at different Alert Levels (e.g., Auckland often had stricter rules).

- **During the initial COVID-19 outbreak and subsequent national lockdown,** in-person school research activities were paused. This included any engagement requiring physical presence in school settings. As the country moved through different Alert Levels, re-engaging with schools depended on the local alert levels. Research activities could resume in areas under lower Alert Levels with appropriate safety measures in place (Auckland often had stricter rules).
- **April - May 2020:** Schools remained closed through the Alert Level 3 period from 27 April until a shift to Level 2 on 14 May saw schools begin to reopen with strict health and safety protocols.
- **August 2020:** Auckland faced heightened restrictions when community transmission re-emerged. From 12 August, Auckland moved back to Alert Level 3, necessitating another round of school closures, partially eased to Level 2.5 at the end of August.
- **February 2021:** Auckland schools faced closures again due to Alert Level changes, moving between Levels 3 and 2 in response to new cases, leading to brief disruptions in February.
- **August 2021 - March 2022:** The emergence of the Delta variant led to sustained school closures from 17 August 2021, as Auckland moved to Alert Level 4. Schools stayed closed or operated under significant restrictions until late 2021. Even as the rest of the country adjusted levels, Auckland's restrictions were more prolonged due to higher transmission rates.
- **2022 School Year:** The shift to the Red Alert Level in January 2022, followed by the transition to Orange in April 2022, enhanced overall school functions, facilitating face-to-face instruction under health guidelines. Despite these advancements, external researchers were still restricted when researching school grounds during this period.

As the epicentre of several COVID-19 outbreaks, Auckland faced the most prolonged and most stringent restrictions regarding school operations. While affected by

nationwide and local alert levels, the rest of NZ generally experienced less severe and less frequent disruptions. A proactive approach by the government and health officials worked to balance educational needs and public health, leading to variations in school closure impacts across regions.

The PI faced multiple layers of restrictions: government-imposed limitations preventing research in schools during Levels 2-4 or Red/Orange alert phases, compounded by Massey University's own Health and Safety protocols for research activities during those times.

These constraints delayed both empirical data collection phases and limited the number of participants the PI could engage with and the manner of those engagements. The closures resulted in a substantial recalibration of the research timeline and methodology. This period required a significant pivot to adapting research strategies to fit the ever-changing guidelines. Despite these hurdles, the study has maintained its integrity and focus, even as it necessitated a more iterative and flexible approach to complete the research objectives under these extraordinary circumstances.

Appendix E

Meteorological analysis

This appendix presents the meteorological analysis supporting specific sections of the main text. The following correlations are established:

- **Section E.1** corresponds to the analysis in Chapter 5, **Section 5.4**
- **Section E.2** underpins the findings discussed in Chapter 6, **Section 6.3.3**

E.1 Auckland - 29/8/2022 to 25/6/2024

Section E.1 corresponds to the analysis in Chapter 5, **Section 5.4**

Table E.1 focuses on the core school week, spanning from 09:00 on Monday to 15:00 on Friday. The data is examined on a term-by-term basis, as illustrated in Appendices D **Tables D.2** to **D.6**. This approach provides a comprehensive overview of the environmental conditions throughout each season, capturing the typical patterns and variations that occur during regular school hours across different times of the year.

The term-by-term breakdown enables the identification of seasonal trends and fluctuations in indoor environmental parameters. This granular approach facilitates a nuanced understanding of how factors such as temperature, humidity, and CO₂ levels may vary across different times of the year, providing valuable insights required for Chapters 6 and 7.

TABLE E.1: Seasonal Meteorological Data Overview for Auckland (2022-2024)

Season	Temperature (°C)	Relative Humidity (%)	Rain (mm)	Windspeed (km/h)	Cloud cover (%)	Solar Radiation (kW/m ²)
Winter '22	12.76 [2.20]	84.09 [6.50]	4.99 [7.76]	23.77 [10.87]	59.86 [26.85]	122.04 [57.35]
Spring '22	15.19 [2.36]	79.34 [8.51]	4.32 [9.26]	27.67 [8.58]	64.64 [20.91]	194.01 [73.72]
Summer '23	19.71 [1.46]	82.62 [6.75]	8.38 [13.05]	30.78 [10.67]	55.11 [25.80]	211.46 [86.72]
Autumn '23	17.04 [2.40]	82.50 [7.19]	4.54 [9.75]	28.89 [9.71]	47.71 [25.10]	146.84 [74.48]
Winter '23	11.71 [1.59]	83.66 [6.02]	3.13 [5.69]	27.32 [10.11]	51.74 [23.24]	103.09 [40.21]
Spring '23	15.13 [1.73]	79.70 [7.25]	2.92 [5.60]	29.80 [8.35]	63.59 [23.88]	200.48 [70.17]
Summer '24	20.08 [1.03]	73.12 [6.62]	0.93 [2.56]	27.47 [8.75]	39.62 [27.17]	263.29 [79.40]
Autumn '24	15.78 [2.65]	79.39 [7.01]	3.13 [7.53]	27.19 [9.90]	54.12 [25.60]	149.67 [61.68]
Winter '24	12.02 [2.18]	84.00 [6.31]	3.98 [9.33]	22.32 [9.82]	51.00 [30.12]	85.82 [30.26]

Ambient temperature (Figure E.1)

FIGURE E.1: Average Seasonal Temperatures with Error Bars (Winter 2022 - Winter 2024)

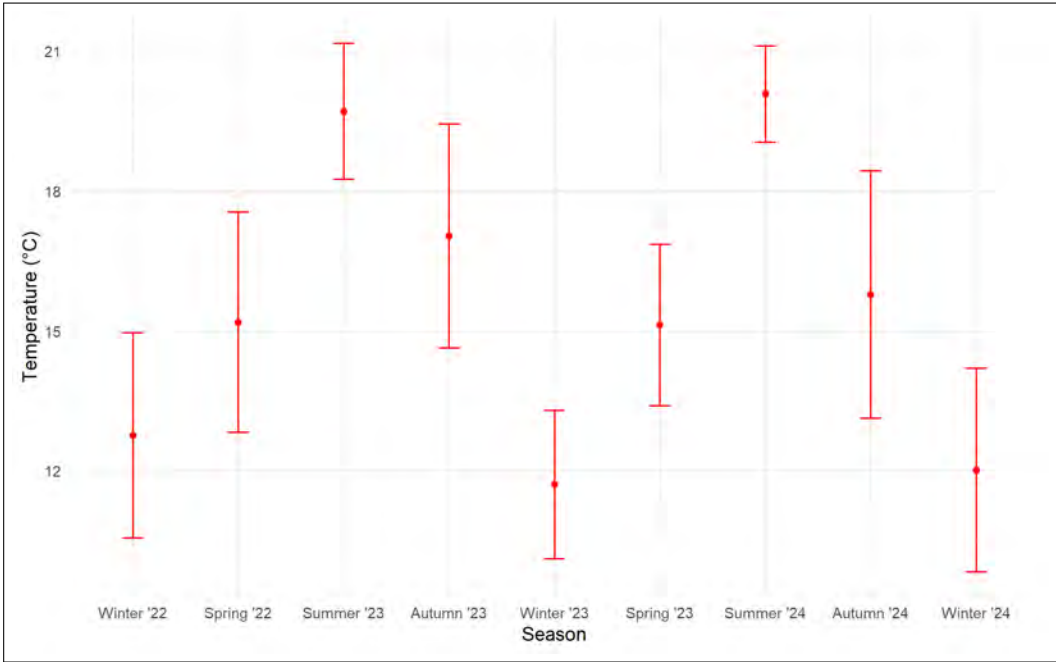


Figure E.1 illustrates seasonal temperature variations in Auckland from Winter 2022 to Winter 2024, revealing distinct patterns and potential outliers. During Winter, temperatures averaged around 15 °C in 2022 but dropped to 13-14 °C in 2023 and 2024. Spring seasons showed moderate increases from Winter, with temperatures around 16-17 °C in both 2022 and 2023. The hottest temperatures were observed during the Summers of 2023 and 2024, peaking at 20-21 °C and demonstrating less

variability. Autumn temperatures were intermediate, around 18 °C, though Autumn 2023 was slightly warmer than Autumn 2024.

Consistent cyclic patterns emerged: Winters were the coldest, Summers the warmest, and Springs and Autumns exhibited transitional temperatures. Summers had smaller error margins, indicating more stable temperatures, while Autumn and Winters displayed more significant variability. Potential outliers include the slightly higher temperature in Autumn 2023 compared to Autumn 2024 and the notably lower temperature in Winter 2024 than in previous Winters. These insights help us understand Auckland’s seasonal temperature fluctuations and highlight anomalies that may require further investigation.

Relative humidity (Figure E.2)

FIGURE E.2: Seasonal Variations in Relative Humidity in Auckland (Winter 2022 - Winter 2024)

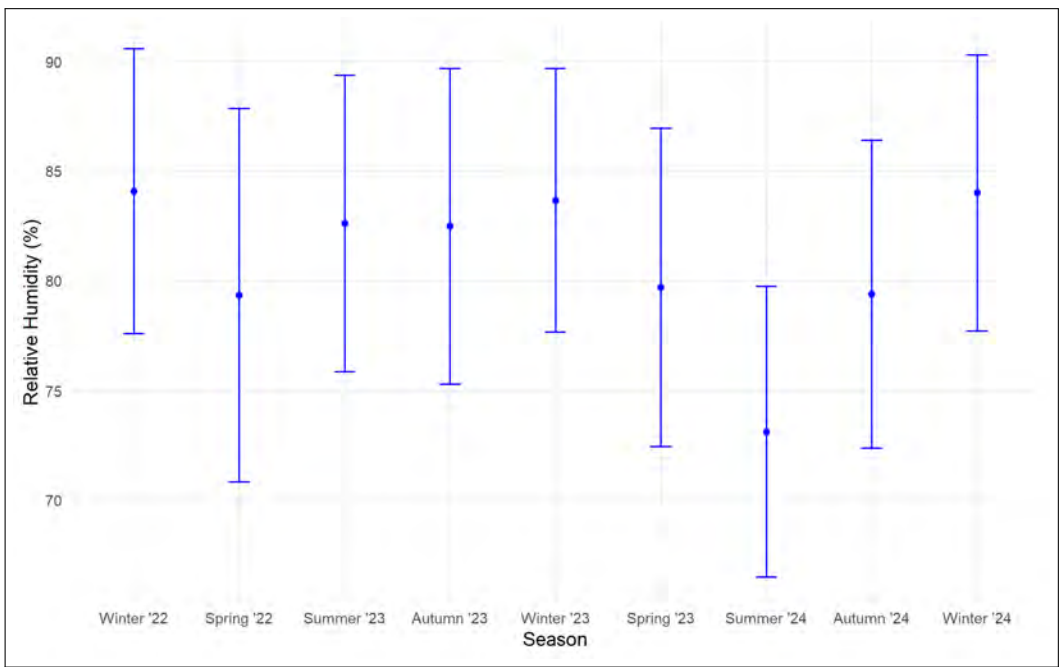


Figure E.2 displays seasonal RH variations in Auckland from Winter 2022 to 2024, highlighting distinct patterns and potential outliers. Winters (2022, 2023, and 2024) consistently exhibit high RH, around 85%, with moderate variability. Spring seasons (2022 and 2023) show slightly lower RH values, averaging 80-85%, but with noticeable variability. Summer seasons (2023 and 2024) demonstrate the lowest RH

values, between 75-85%, and the highest variability among all seasons, indicating significant fluctuations. Autumns (2023 and 2024) have intermediate RH values, similar to Spring, around 80-85%, with substantial variability.

Cyclic patterns are evident, with the highest RH in Winter, moderate RH in Spring, lowest RH in Summer, and intermediate RH in Autumn. The variability in Summer seasons suggests possible anomalies or significant fluctuations in RH, marking them as potential outliers. Overall, the observations highlight higher RH during cooler months and lower, more variable RH during warmer months, with transitional values in Spring and Autumn.

Rainfall (Figure E.3)

FIGURE E.3: Seasonal Variations in Rainfall (2022-2024)

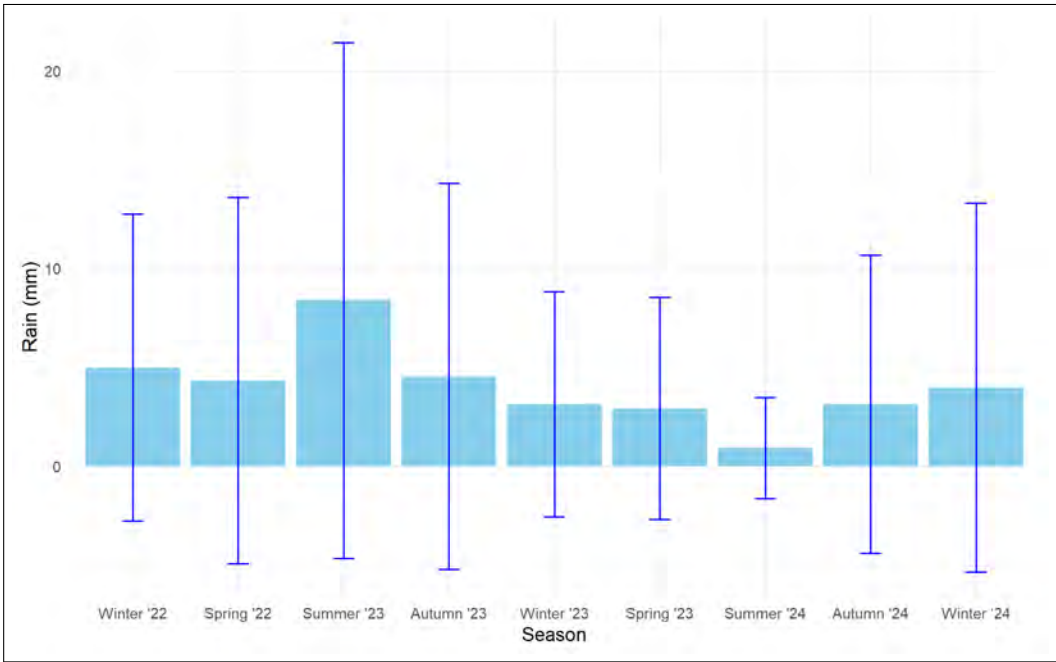


Figure E.3 illustrates the seasonal rainfall trends from Winter 2022 to Winter 2024, revealing significant variability across different seasons. Notably, Summer 2023 experienced the highest rainfall at around 15 mm, marking an outlier (resulting from Cyclone Gabrielle). Winters and Autumn mostly displayed moderate rainfall ranging from 7-10 mm but with high variability, as suggested by large error bars. In contrast, Spring 2022 and Spring 2023 had relatively lower rainfall, averaging around 5 mm,

yet still exhibited substantial fluctuation. Summer 2024 presented a sharp decrease in rainfall, near 2-3 mm, highlighting another potential outlier. Overall, the data indicates that while Summers generally tend to have higher rainfall, the rainfall amounts are highly unpredictable and subject to wide fluctuations across all seasons.

Windspeed (Figure E.4)

FIGURE E.4: Seasonal Variations in Wind Speed (2022-2024)

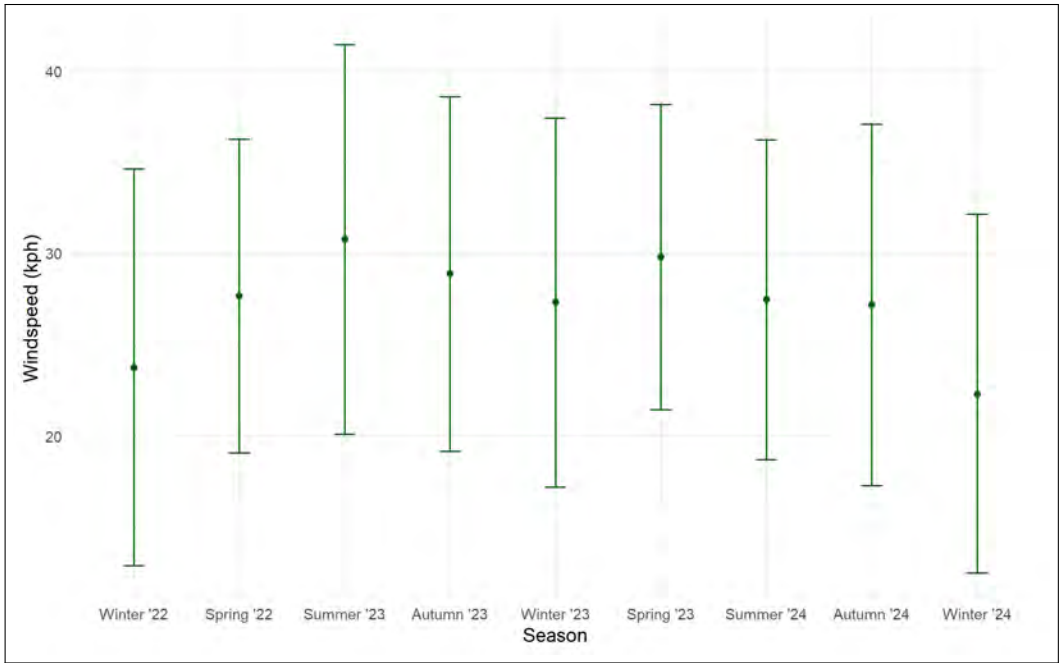


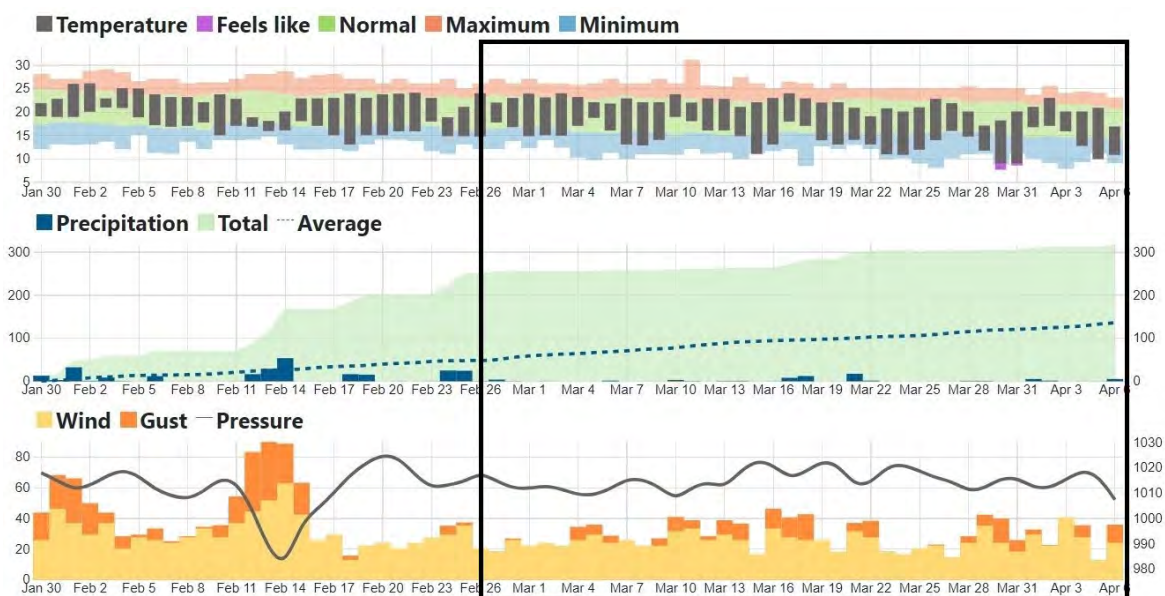
Figure E.4 provides an overview of the seasonal variations in wind speeds from Winter 2022 to Winter 2024, showing an average wind speed of approximately 30 kph across all seasons. Notably, significant variability is indicated by the large error bars, which range from around 20 kph to 40 kph, reflecting the unpredictable nature of wind conditions throughout the year. Despite consistent average wind speeds, each season exhibits wide fluctuations, with no distinct outliers, as the ranges overlap substantially. This suggests that while the average wind speed remains stable, individual readings can vary widely within any given season, highlighting the inherent variability in wind patterns over the observed period.

E.2 Auckland - Term 1 2023 vs 2024

Section E.2 underpins the findings discussed in Chapter 6, Section 6.3.3

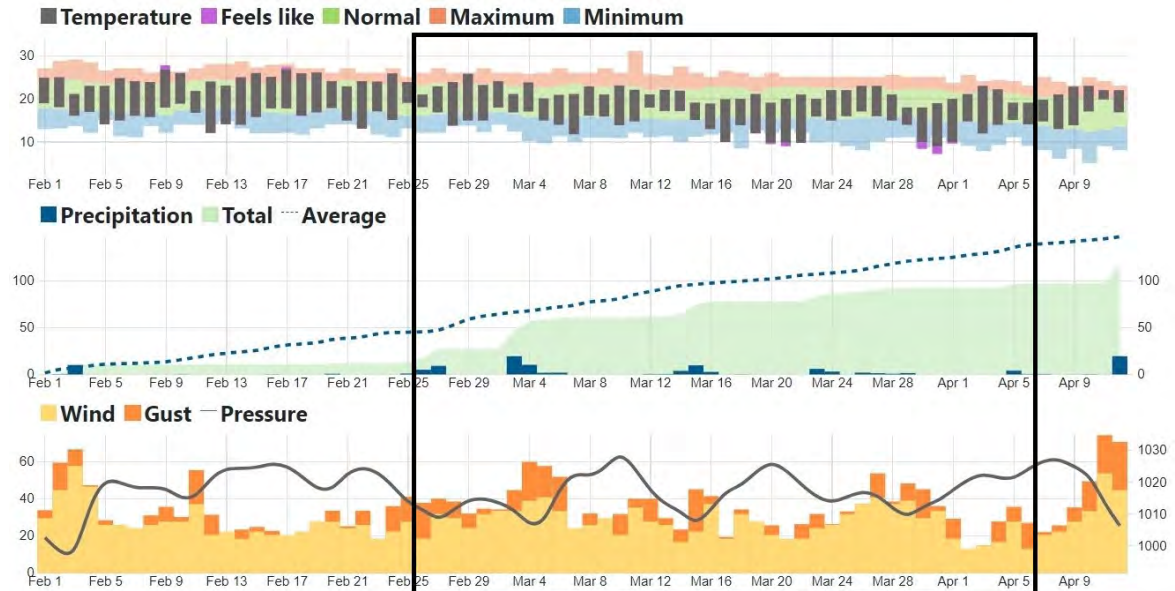
The meteorological conditions for Term 1 (for 2023 to 2024) are illustrated in **Figures E.5 and E.6**, with the (mean and [standard deviation]) provided in **Table E.2**. These figures provide a detailed representation of weather patterns, temperature variations, precipitation levels, and wind speeds over the specified terms. Particular attention will be given to the regions encased in the black boxes within the figure, as these areas are of significant interest for further analysis. The specific dates can be referenced in the **Table** in Appendices D. This focused review will enable understanding the meteorological anomalies and trends pertinent to these two terms.

FIGURE E.5: *Temperature, Rainfall and Wind Conditions for Auckland Term One 2023*



Source: <https://www.visualcrossing.com/weather-history/Auckland>

FIGURE E.6: Temperature, Rainfall and Wind Conditions for Auckland Term One 2024



Source: <https://www.visualcrossing.com/weather-history/Auckland>

TABLE E.2: Temperature, Relative Humidity, Rainfall, Windspeed and Cloud Cover for Auckland Term One (2023-2024)

2023							
Term One	TempMax (°C)	TempMin (°C)	Temp (°C)	Relative	Rainfall (mm)	Windspeed	Cloud Cover
Weeks	Mean [SD]	Mean [SD]	Mean [SD]	Humidity (%)	Mean [SD]	(kph)	(%)
5	23.20 [0.72]	15.92 [1.17]	19.16 [0.10]	84.5 [2.49]	0.93 [1.57]	22.60 [2.48]	32.50 [19.36]
6	22.54 [0.72]	15.04 [2.28]	18.98 [0.79]	80.0 [2.31]	0.97 [1.28]	25.26 [3.48]	43.84 [29.38]
7	22.60 [0.96]	14.64 [2.38]	18.44 [1.41]	77.62 [8.50]	2.01 [3.08]	26.64 [5.61]	44.20 [30.56]
8	20.60 [0.98]	12.44 [1.27]	16.52 [0.67]	78.20 [5.77]	3.78 [6.80]	22.56 [6.00]	24.10 [14.72]
9	19.48 [1.66]	12.16 [2.84]	15.96 [2.02]	75.84 [9.24]	0.38 [0.47]	23.34 [6.95]	38.88 [28.21]
10	20.18 [1.93]	12.90 [2.25]	16.38 [1.30]	79.28 [5.79]	1.97 [2.36]	27.00 [8.93]	31.74 [22.04]

2024							
Term One	TempMax (°C)	TempMin (°C)	Temp (°C)	Relative	Rainfall (mm)	Windspeed	Cloud Cover
Weeks	Mean [SD]	Mean [SD]	Mean [SD]	Humidity (%)	Mean [SD]	(kph)	(%)
5	23.36 [1.55]	15.76 [1.53]	19.46 [0.38]	78.36 [6.25]	2.86 [3.74]	27.08 [5.15]	40.70 [34.67]
6	21.76 [1.37]	14.80 [1.82]	18.26 [1.34]	73.52 [8.09]	2.81 [3.83]	32.62 [6.68]	68.14 [15.00]
7	21.24 [1.14]	16.46 [1.27]	18.80 [0.85]	86.36 [4.90]	2.88 [3.71]	25.56 [6.17]	77.42 [11.57]
8	20.24 [0.73]	11.06 [1.65]	15.60 [0.94]	69.20 [5.34]	0.04 [0.08]	23.34 [5.39]	24.62 [25.99]
9	21.40 [1.85]	15.62 [1.04]	18.28 [1.24]	77.10 [4.13]	1.11 [0.67]	37.10 [3.01]	60.74 [6.73]
10	21.08 [1.41]	13.18 [1.92]	17.12 [0.72]	76.48 [3.30]	0.81 [1.61]	18.10 [5.12]	61.84 [18.40]

- **Maximum temperatures:** Generally, Week 5 and Week 9 of 2024 are slightly warmer than 2023, while Weeks 6, 7, and 8 tend to be cooler or about the same.

- **Minimum temperatures:** Week 7 of 2024 shows a significant rise compared to 2023, while Week 8 shows a significant decrease. Other weeks do not show major variances.
- **Temperature:** Week 9 of 2024 shows the most significant increase in overall temperature. Weeks 5 and 10 also show a moderate increase. Weeks 6 and 8 are cooler, while Week 7 slightly increases.
- **RH** generally decreased in 2024 compared to 2023, except for Weeks 7 and 9, where there was a noticeable increase.
- Most weeks in 2024 experienced an increase in **rainfall** compared to 2023, with Week 8 being a significant exception where rainfall dropped drastically.
- **Windspeed** increased notably in most weeks of 2024 compared to 2023, particularly in Weeks 5, 6, and 9. Week 10 saw a notable decrease in windspeed in 2024.
- **Cloud cover** was considerably higher in most weeks of 2024 compared to 2023, with Weeks 6, 7, 9, and 10 showing particularly significant increases.

In summary:

1. Overall, there are fluctuations between the two years, with certain weeks exhibiting notable differences in maximum, minimum, and mean temperatures.
2. RH generally decreased in 2024, with the exceptions of Weeks 7 and 9.
3. Rainfall increased in most weeks, particularly significant in Weeks 5, 6, and 7.
4. Windspeed generally increased, with noticeable spikes in Weeks 5, 6, and 9, but decreased in Week 10.
5. Cloud cover significantly increased in most weeks, with substantial differences in Weeks 6, 7, 9, and 10.

The meteorological conditions in **Table E.1** influence window-opening behaviour in various ways.

- Winter

- Temperature (11.7 °C to 12.7 °C): Low temperatures may discourage opening windows to maintain indoor warmth. Limited window openings could mean less ventilation.
 - Relative Humidity (83% to 84%): High humidity may lead to discomfort if windows are kept closed. Some ventilation could be necessary to prevent dampness.
 - Rain (3.1 mm to 4.9 mm): Moderate rainfall might limit window opening to avoid water ingress.
 - Windspeed (22.3 to 27.3 kph): Moderate wind speeds may support opening windows slightly to balance airflow without creating drafts.
 - Cloud Cover (51% to 59%): High cloud cover often correlates with less solar heat gain, making temperature control through window opening critical.
 - Solar Radiation (85.8 to 122.1 kW/m²): Low solar radiation decreases passive heating, lessening the incentive to open windows during the day for cooling.
- Spring
 - Temperature (15.1 °C to 15.1 °C): Moderate temperatures are conducive to more frequent window opening for fresh air.
 - Relative Humidity (79% to 79%): Comfortable humidity levels make window openings beneficial for ventilation.
 - Rain (2.92 mm to 4.3 mm): Similar to Winter, moderate rain might occasionally limit window opening but generally allows for ventilation when not raining.
 - Windspeed (27.6 to 29.8 kph): Higher wind speeds support effective natural ventilation, especially during pleasant weather.
 - Cloud Cover (63% to 64%): Moderate cloud cover is balanced, often making window openings desirable for daylight and fresh air.
 - Solar Radiation (194.1 to 200.4 kW/m²): Increased solar energy can warm classrooms, leading to window openings to maintain comfort.

- Summer

- Temperature (19.7 °C to 20.8 °C): Higher temperatures encourage keeping windows open to allow cooler air in or facilitate ventilation.
- Relative Humidity (73% to 82%): Higher humidity may necessitate more frequent window opening to improve air circulation.
- Rain (0.9 mm to 8.3 mm): High rainfall variability could mean windows need to be strategically opened during dry periods to ensure ventilation while avoiding water ingress during rain.
- Windspeed (27.4 to 30.7 kph): Consistent and higher wind speeds are beneficial for effective ventilation, encouraging window opening to allow fresh air movement.
- Cloud Cover (39% to 55%): Lower cloud cover and more sunlight might require windows to be opened to avoid overheating and ensure fresh air flow.
- Solar Radiation (211.4 to 263.2 kW/m²): High solar radiation can cause indoor overheating, necessitating window openings for cooling purposes, especially during peak sunlight hours.

- Autumn

- Temperature (15.7 °C to 17.4 °C): Moderate temperatures are generally comfortable, encouraging frequent window opening for ventilation.
- Relative Humidity (79% to 82%): Similar to Spring, manageable humidity levels support ventilation through window openings.
- Rain (3.1 mm to 4.5 mm): Moderate rain may occasionally limit window opening but generally allows for sufficient ventilation during dry periods.
- Windspeed (27.1 to 28.8 kph): Adequate wind speeds support effective indoor ventilation, encouraging window opening to ensure air quality.
- Cloud Cover (47% to 54%): Moderate cloud cover makes it reasonable to open windows for daylight and fresh air without significant risk of heating problems.
- Solar Radiation (146.8 to 149.6 kW/m²): Moderate solar radiation provides a balance, allowing for comfortable indoor temperatures with strategic window opening.

Appendix F

IEM reporting - pre-COVID-19

This appendix presents the indoor environmental monitoring analysis supporting specific sections of the main text. The following correlations are established:

- **Section F.1** provides IEM data for Chapter 5, **Section 5.3.2** Hawke's Bay
- **Section F.2** corresponds to the analysis in Chapter 5, **Section 5.3.2** Christchurch
- **Section F.3** underpins the findings discussed in Chapter 5, **Section 5.3.2** Dunedin

F.1 Hawke's Bay

Table F.1 displays the average weekly temperature, RH, and CO₂ levels during school hours (Monday 09:00 to Friday 15:00) for two schools in Hawke's Bay (H1 and H2). 15% of data is missing for classroom H1-1 in both Summer and Winter and for classroom H1-2 in Summer. This missing data indicates that it was not successfully transferred to the Massey University server.

TABLE F.1: *Temperature, Relative Humidity and CO₂ Mean [SD] in Hawke's Bay Schools*

School_id	Room_id	Season	Temperature (°C)	Relative humidity (%)	Carbon dioxide (ppm)
H1	1	Spring	22.61 [1.66]	50.95 [3.30]	888.56 [213.79]
		Summer	NA	NA	NA
		Autumn	24.01 [1.25]	53.53 [4.88]	941.58 [397.53]
		Winter	NA	NA	NA
H1	2	Spring	22.97 [1.20]	48.16 [3.16]	1084.79 [664.59]
		Summer	NA	NA	NA
		Autumn	20.94 [1.03]	57.42 [7.10]	1615.62 [706.58]
		Winter	17.32 [1.92]	66.30 [3.45]	1234.52 [694.58]
H2	1	Spring	22.20 [1.36]	58.16 [1.37]	739.02 [196.12]
		Summer	23.40 [1.57]	63.95 [8.21]	1392.52 [580.24]
		Autumn	22.77 [1.12]	64.47 [3.59]	1223.00 [620.95]
		Winter	20.25 [2.44]	56.57 [5.34]	1533.29 [792.49]
H2	2A	Spring	23.36 [0.97]	58.15 [1.75]	1273.16 [549.26]
		Summer	24.16 [0.83]	62.36 [6.68]	1969.68 [812.52]
		Autumn	23.06 [0.98]	62.90 [3.05]	1319.72 [560.69]
		Winter	20.64 [2.43]	55.00 [6.64]	1376.01 [738.03]
H2	2B	Spring	22.94 [1.32]	58.39 [1.75]	1164.46 [521.01]
		Summer	24.25 [0.78]	62.02 [6.67]	1988.21 [824.05]
		Autumn	23.05 [0.99]	63.03 [3.07]	1312.82 [557.70]
		Winter	20.72 [2.30]	54.92 [6.36]	1402.71 [750.00]

In classroom H2-2, two duplicate IEM units (2A and 2B) have been installed for quality control.

Table F.1 from two schools in Hawke's Bay indicate that children mainly experienced comfortable temperatures and RH, though Classroom H1-2 had slightly lower Winter temperatures than WHO recommendations. CO₂ levels were concerning, with only 30% of measurements below the 1000 ppm recommended level. Students in Classroom H2-2(A and B) faced high CO₂ levels year-round, peaking at around 2000 ppm in Summer.

Classroom H1-1 maintained moderate CO₂ levels in Spring and Autumn but lacked Summer and Winter data. H1-2 experienced consistent warmth with high humidity and CO₂ levels, indicating a need for better Winter ventilation. H2-1 generally maintained comfortable temperatures across seasons but had elevated CO₂ levels,

especially in Winter and Summer. H2-2B faced high humidity and CO₂ levels in Summer and Winter, suggesting the need for balanced ventilation and heating.

F.1.1 Temperature

Classrooms comparison

Classroom H1-1 is at risk, particularly in Autumn, where only 49% of the time is within the comfort zone. In Spring, 27% of the time, exceeds the recommended comfort zone, potentially causing discomfort. Classroom H1-2 performs well in Autumn with 100% of the time within the comfort zone. However, during Winter, there is significant discomfort due to cold temperatures, with only 45% within the comfort zone. Classroom H2-1 shows good performance, with 86% of the time within the comfort zone in Autumn. However, there is some discomfort in Winter, with 9% below 16 °C.

Seasonal trends

Classroom H2-2A has some seasonal trends. It performs well in Autumn and Spring, with over 77% within the comfort zone. However, in Summer, only 47% of the time is within the comfort zone, causing significant discomfort. Similarly, in Winter, cold discomfort occurs 20% of the time. Classroom H2-2B, the duplicate IEM for quality assurance, shows similar trends to H2-2A. It performs well in Autumn, with 88% within the comfort zone. However, in Summer, only 42% of the time is within the comfort zone, and in Winter, cold discomfort occurs 20% of the time.

F.1.2 Relative humidity

Classrooms at risk

1. H2-1: Struggles significantly in Summer and Autumn
2. H2-2A and H2-2B: Perform poorly in Summer and Autumn

Classrooms performing better

- H1-1: Performs well in Spring and Autumn
- H1-2: Performs exceptionally in Spring, though it has issues in Autumn and Winter

Seasonal trends

- Spring: Generally good performance across all classrooms
 - H1-1, H1-2, and H2-1 maintain ideal RH for 86-100% of the time
 - H2-2A and H2-2B maintain ideal RH for about 81-82% of the time
- Summer: Problematic for most classrooms with data
 - H2-1, H2-2A, and H2-2B struggle to maintain ideal RH (only 39-43% of the time)
- Autumn: Challenging for most classrooms
 - H1-1 performs well (89% ideal RH)
 - H1-2, H2-1, H2-2A, and H2-2B struggle significantly (11-72% ideal RH)
- Winter: Mixed performance
 - H2-1 performs well (79% ideal RH)
 - H2-2A and H2-2B perform moderately well (60-62% ideal RH)
 - H1-2 performs poorly (only 3% ideal RH)

Spring seems to be the best season for maintaining ideal RH across all classrooms, while Summer and Autumn present the most challenges. Winter performance varies significantly between classrooms.

F.1.3 Carbon dioxide

Classrooms at risk

1. Classroom H1-2

- Spring: 21% of the time CO₂ levels exceed the 1500 ppm limit.
- Autumn: 58% of the time CO₂ levels exceed the 1500 ppm limit.
- Winter: 36% of the time CO₂ levels exceed the 1500 ppm limit.

2. Classroom H2-1

- Summer: 39% of the time CO₂ levels exceed the 1500 ppm limit.

- Autumn: 26% of the time CO₂ levels exceed the 1500 ppm limit.
- Winter: 56% of the time CO₂ levels exceed the 1500 ppm limit.

3. Classroom H2-2A

- Spring: 31% of the time CO₂ levels exceed the 1500 ppm limit.
- Summer: 66% of the time CO₂ levels exceed the 1500 ppm limit.
- Autumn: 31% of the time CO₂ levels exceed the 1500 ppm limit.
- Winter: 46% of the time CO₂ levels exceed the 1500 ppm limit.

4. Classroom H2-2B

- Spring: 24% of the time CO₂ levels exceed the 1500 ppm limit.
- Summer: 67% of the time CO₂ levels exceed the 1500 ppm limit.
- Autumn: 31% of the time CO₂ levels exceed the 1500 ppm limit.
- Winter: 45% of the time CO₂ levels exceed the 1500 ppm limit.

Classrooms performing well

1. Classroom H1-1

- Spring: 69% of the time CO₂ levels are below 1000 ppm.
- Autumn: 83% of the time CO₂ levels are below 1000 ppm.

2. Classroom H2-1

- Spring: 87% of the time CO₂ levels are below 1000 ppm. This classroom performs very well in Spring.

Seasonal trends

1. Spring:

- Classrooms H1-1 and H2-1 perform well, both maintaining lower CO₂ levels most of the time.
- Classrooms H2-2A and H2-2B still show some risk, with a significant portion of time exceeding the 1500 ppm limit.

2. Summer:

- CO₂ levels are a concern in both H2-1 and H2-2 classrooms. The H2-2 series has a high percentage of time exceeding the 1500 ppm limit.

3. Autumn:

- Classroom H1-2 and the entire H2 series show considerable risk, with a notable percentage of time spent over the 1000 ppm and 1500 ppm thresholds.

4. Winter:

- Classrooms H1-2, H2-1, H2-2A, and H2-2B show elevated CO₂ levels with a concerning percentage of time exceeding the 1500 ppm limit.

The same format will be utilised to present the results of Christchurch and Dunedin schools.

F.2 Christchurch

Table F.2 and **Table F.3** display the weekly average temperature, RH, and CO₂ levels during school hours (Monday 09:00 to Friday 15:00) for the four schools situated in Christchurch (C1, C2, C3, and C4). A 21% data loss occurred over this period via the IEM platform and transmission with the server; however, a backup was made on the platform's SD card.

TABLE F.2: *Temperature, Relative Humidity and CO₂ Mean [SD] in Christchurch Schools (Part 1)*

School_id	Room_id	Season	Temperature (°C)	Relative humidity (%)	Carbon dioxide (ppm)
C1	1	Spring	21.24 [1.13]	47.10 [2.93]	1478.78 [479.44]
		Summer	22.98 [0.90]	53.52 [4.01]	1309.13 [352.28]
		Autumn	21.33 [0.65]	60.52 [1.08]	1371.33 [162.91]
		Winter	21.80 [1.52]	51.79 [5.42]	1633.54 [393.13]
C1	2	Spring	NA	NA	NA
		Summer	24.14 [0.75]	52.81 [4.33]	1498.81 [323.23]
		Autumn	NA	NA	NA
		Winter	21.40 [1.16]	55.19 [6.02]	2019.27 [412.55]
C1	5	Spring	21.42 [1.74]	49.12 [5.29]	1897.05 [834.43]
		Summer	NA	NA	NA
		Autumn	21.38 [0.87]	58.40 [2.58]	1148.76 [294.61]
		Winter	19.92 [0.32]	67.95 [0.78]	2865.59 [69.93]
C2	1	Spring	22.29 [1.69]	44.78 [5.21]	1497.85 [596.21]
		Summer	24.20 [2.11]	56.42 [5.49]	1908.82 [536.36]
		Autumn	NA	NA	NA
		Winter	NA	NA	NA
C2	2	Spring	22.54 [2.04]	39.08 [4.44]	851.50 [253.52]
		Summer	NA	NA	NA
		Autumn	NA	NA	NA
		Winter	9.45 [1.32]	81.17 [2.72]	526.05 [55.07]
C2	3	Spring	20.24 [1.46]	44.61 [4.62]	767.98 [253.25]
		Summer	NA	NA	NA
		Autumn	NA	NA	NA
		Winter	NA	NA	NA

TABLE F.3: *Temperature, Relative Humidity and CO₂ Mean [SD] in Christchurch Schools (Part 2)*

School_id	Room_id	Season	Temperature (°C)	Relative humidity (%)	Carbon dioxide (ppm)
C3	2	Spring	20.95 [1.11]	46.83 [4.97]	1325.17 [734.92]
		Summer	25.51 [1.13]	65.33 [4.98]	927.57 [352.94]
		Autumn	21.13 [0.40]	54.75 [2.63]	617.78 [133.44]
		Winter	22.34 [0.78]	49.83 [5.13]	1938.8 [696.71]
C3	3	Spring	20.90 [1.64]	44.60 [6.41]	911.06 [457.06]
		Summer	24.06 [1.02]	52.26 [3.20]	2173.77 [586.75]
		Autumn	NA	NA	NA
		Winter	18.45 [1.47]	49.80 [3.13]	1205.28 [482.90]
C3	4	Spring	22.37 [1.72]	46.69 [5.95]	1824.00 [789.26]
		Summer	25.51 [0.86]	48.59 [3.38]	2837.07 [769.30]
		Autumn	22.92 [0.41]	66.23 [0.69]	3789.73 [321.61]
		Winter	20.69 [1.17]	59.37 [5.35]	2594.31 [1001.49]
C4	1	Spring	20.38 [2.16]	45.09 [4.08]	815.03 [241.23]
		Summer	26.15 [1.97]	58.29 [6.95]	670.47 [217.25]
		Autumn	21.17 [0.45]	56.66 [2.40]	773.45 [123.57]
		Winter	21.71 [1.33]	49.04 [3.94]	1719.43 [948.82]
C4	2	Spring	18.46 [2.30]	45.41 [4.74]	633.27 [195.00]
		Summer	24.06 [1.55]	64.49 [8.45]	545.10 [108.86]
		Autumn	19.40 [0.55]	65.51 [2.13]	1412.63 [128.93]
		Winter	11.23 [1.93]	68.11 [2.00]	452.06 [17.95]
C4	3A	Spring	21.27 [1.25]	41.04 [5.70]	586.55 [129.50]
		Summer	26.36 [1.47]	59.58 [6.89]	606.23 [135.04]
		Autumn	21.59 [0.49]	52.74 [2.61]	657.13 [59.11]
		Winter	23.62 [0.98]	38.89 [3.24]	806.03 [267.72]
C4	3B	Spring	21.63 [1.28]	40.29 [5.46]	591.25 [126.43]
		Summer	26.76 [1.47]	58.53 [6.64]	602.48 [133.90]
		Autumn	21.95 [0.53]	51.80 [2.53]	650.19 [58.59]
		Winter	24.07 [0.96]	37.90 [3.14]	811.94 [267.20]

In classroom C4-3, two duplicate IEM units (3A and 3B) have been installed for quality control.

The four Christchurch schools (12 classrooms) studied the averages over the selected weeks, which show that during the deployment, children were generally exposed to comfortable temperature and relative humidity levels across all four seasons, except for Classrooms C2-2 and C4-2 in Winter. In these classrooms, Winter averages were 9.4 °C and 81%, and 11.2 °C and 68%, respectively, with low CO₂ levels near outdoor values, suggesting they were unoccupied during those periods.

Out of 38 CO₂ average measurements, 44% were below or around 1000 ppm, while 20 exceeded the MoE's threshold of 1200 ppm. Classroom C3-4 exhibited high CO₂ levels year-round, reaching 2837 ppm in Summer and 3789 ppm in Autumn, indicating poor ventilation. In contrast, lower CO₂ levels in School C4 during Spring and Summer suggested better ventilation practices in those seasons.

F.2.1 Temperature

Classrooms at risk

- C1-2: Performs poorly in Summer with only 46% of time within the desired range.
- C2-1: Struggles in both Spring and Summer, with significant time above 24 °C.
- C2-2: Performs poorly in Spring and completely fails in Winter, with 100% of time below 16 °C.

Classrooms performing better

- C1-1: Performs well across all seasons, with perfect performance in Spring and Autumn.
- C1-5: Performs well in all measured seasons, with perfect performance in Autumn and Winter.
- C2-3: Performs well in Spring, the only season measured.
- C3-2: Performs well in Spring, Autumn, and Winter.
- C3-4: Performs well in Autumn and Winter and mostly well in Spring.
- C4-1: Performs well in Autumn and mostly well in Spring and Winter.
- C4-3A: Performs perfectly in Spring and Autumn.
- C4-3B: Performs well in Spring and Autumn and partially well in Summer.

Seasonal trends

- Summer: Generally the most challenging season, with classrooms often exceeding 24 °C (C1-1, C1-2, C2-1).
- Winter: Mixed performance - some classrooms perform well (C1-1, C1-2, C1-5), while others struggle (C2-2).
- Spring and Autumn: Generally better performance across classrooms, with many meeting or coming close to meeting the criteria.
- Summer: Consistently the most challenging season across all classrooms, with most failing to meet the criteria due to high temperatures.
- Winter: Mixed performance - some classrooms perform well (C3-2, C3-4, C4-1), while others struggle (C4-2, C4-3B).
- Spring and Autumn: Generally better performance across classrooms, with many meeting or coming close to meeting the criteria. Autumn particularly shows excellent performance in all classrooms.

Classrooms at risk

- C3-2: Performs very poorly in Summer with only 16% of time within the desired range.
- C3-3: Struggles in Summer and Winter, with significant time above 24 °C in both seasons.
- C3-4: Performs extremely poorly in Summer with only 6% of time within the desired range.
- C4-1: Struggles in Summer with only 20% of the time within the desired range and 18% above 28 °C.
- C4-2: Performs poorly in Spring and Summer and completely fails in Winter with 100% of time below 16 °C.
- C4-3A: Performs very poorly in Summer with only 8% of time within the desired range.

F.2.2 Relative humidity

Classrooms at risk

- C2-2: Performs poorly in both Spring (57% below optimal range) and Winter (100% above optimal range).
- C1-1: Struggles in autumn with 74% of time above the optimal range.
- C2-1: Has noticeable deficits in Spring (26% below optimal range) and exceedances in Summer (33% above optimal range).
- C4-3A: Performs poorly in Spring, Summer, and Winter, with significant deviations from the optimal range.
- C4-3B: Similar to C4-3A, shows poor performance in Spring, Summer, and Winter.
- C4-2: Struggles significantly in Summer, with notable issues in other seasons.
- C3-4: Has significant issues in Winter, with 52% above the optimal range.

Classrooms performing better

- C1-5: Performs well across all measured seasons, with perfect performance in Winter.
- C1-2: Performs well in both measured seasons, with only slight to noticeable exceedances.
- C2-3: Performs well in Spring, the only season measured.
- C3-3: Performs perfectly in Summer and Winter, with only slight issues in Spring.
- C4-1: Performs well across all seasons, with only minor deviations.
- C3-2: Generally good performance, with some issues in Summer but perfect in Autumn.

Seasonal trends

- Spring: Generally good performance across most classrooms, with C2-2 being the main exception.
- Summer: Mixed performance, with some classrooms showing slight exceedances (C1-1, C1-2) and others more noticeable exceedances (C2-1).
- Autumn: Tends to have higher humidity levels, with C1-1 struggling significantly and C1-5 showing noticeable exceedances.
- Winter: Mixed performance - some classrooms perform very well (C1-5), others have slight issues (C1-1), and C2-2 completely fail to meet the criteria.
- Spring: Most classrooms perform well, with some noticeable deficits (humidity below 40%) in several rooms.
- Summer: Mixed performance, with some classrooms performing well (C3-3, C3-4) and others struggling with low and high humidity (C3-2, C4-2, C4-3A, C4-3B).
- Autumn: Consistently excellent performance across all classrooms, with 100% optimal range in most rooms.
- Winter: Varied performance, ranging from perfect (C3-3, C4-1) to significant issues (C3-4, C4-3A, C4-3B), mostly with high humidity problems.

F.2.3 Carbon dioxide

Classrooms at risk

1. C1-1: Consistently high CO₂ levels across all seasons, often exceeding 1500 ppm.
2. C1-2: High CO₂ levels, especially in Winter.
3. C1-5: Very high CO₂ levels, particularly in Winter.
4. C2-1: High CO₂ levels, especially in Summer.
5. C3-4: Consistently high CO₂ levels across all seasons, with Autumn particularly problematic.

Classrooms performing well

1. C2-2: Consistently low CO₂ levels, mostly below 1000 ppm.
2. C2-3: Low CO₂ levels, with 81% of the time below 1000 ppm in Spring.
3. C4-1: Generally good performance, except for Winter.
4. C4-2: Very good performance, with most seasons having CO₂ levels below 1000 ppm.
5. C4-3A and C4-3B: Excellent performance, with CO₂ levels mostly below 1000 ppm across all seasons.

Seasonal trends

1. Winter tends to have the highest CO₂ levels for most classrooms, likely due to reduced ventilation to maintain warmth.
2. Summer generally shows improved CO₂ levels compared to Winter, possibly due to increased natural ventilation.
3. Spring and Autumn show mixed results, often falling between Winter and Summer in terms of CO₂ levels.
4. Some classrooms (e.g., C3-4) consistently perform poorly across all seasons, indicating potential systemic ventilation issues.
5. Classrooms in building C4 generally perform better across all seasons than other buildings.

F.3 Dunedin

Table F.4 and **Table F.5** display the weekly average temperature, RH, and CO₂ levels during school hours (Monday 09:00 to Friday 15:00) for the four schools situated in Dunedin (D1, D2, D3 and D4). A 7.1% data loss occurred over this period via the IEM platform and transmission with the server; however, a backup was made on the platform's SD card.

TABLE F.4: *Temperature, Relative Humidity and CO₂ Mean [SD] in Dunedin Schools (Part 1)*

School_id	Room_id	Season	Temperature (°C)	Relative humidity (%)	Carbon dioxide (ppm)
D1	1	Spring	22.07 [0.67]	38.12 [2.61]	1058.02 [289.27]
		Summer	24.1 [0.83]	53.31 [3.21]	790.95 [315.04]
		Autumn	22.7 [0.46]	48.28 [0.74]	956.73 [188.03]
		Winter	22.25 [0.55]	42.5 [3.37]	1221.48 [308.30]
D1	2	Spring	19.13 [1.4]	44.47 [2.72]	1255.68 [383.64]
		Summer	23.65 [1.15]	53.04 [3.29]	609.26 [126.20]
		Autumn	21.79 [0.42]	49.04 [0.95]	1005.14 [395.97]
		Winter	20.98 [1.02]	43.01 [2.61]	1070.97 [423.73]
D1	3A	Spring	19.91 [0.93]	41.27 [1.42]	687.91 [149.60]
		Summer	23.81 [0.89]	49.99 [2.37]	496.96 [61.30]
		Autumn	22.2 [0.78]	45.65 [1.75]	845.66 [390.58]
		Winter	NA	NA	NA
D1	3B	Spring	19.8 [0.91]	41.78 [1.42]	680.47 [151.41]
		Summer	23.68 [0.96]	50.66 [2.34]	502.64 [56.58]
		Autumn	22.13 [0.77]	46.08 [1.84]	835.15 [388.63]
		Winter	NA	NA	NA
D1	4	Spring	19.9 [0.93]	45.43 [4.04]	1303.87 [535.62]
		Summer	23.49 [0.92]	58.49 [3.78]	1039.15 [348.64]
		Autumn	19.93 [0.21]	52.14 [1.02]	459.5 [97.01]
		Winter	23.01 [1.34]	38.55 [1.98]	861.42 [257.75]
D2	1	Spring	21.46 [1.83]	36.09 [3.93]	712.36 [172.99]
		Summer	23.74 [2.22]	54.87 [3.70]	515.86 [62.71]
		Autumn	20.9 [0.68]	58.94 [1.75]	1595.81 [200.05]
		Winter	22.19 [2.46]	46.89 [8.53]	1273.66 [340.31]
D2	2	Spring	22.48 [1.74]	37.11 [3.17]	1113.66 [512.64]
		Summer	23.9 [1.33]	53.3 [2.90]	529.94 [88.95]
		Autumn	21.84 [0.50]	50.46 [1.24]	866.08 [179.70]
		Winter	22.62 [2.69]	41.6 [4.73]	1233.91 [373.03]
D2	4	Spring	19.61 [1.36]	42.21 [3.67]	871.2 [215.75]
		Summer	23.37 [1.92]	59.92 [3.24]	991.68 [309.65]
		Autumn	19.8 [0.36]	63.97 [0.65]	783.37 [61.88]
		Winter	19.03 [0.85]	49.35 [3.71]	706.39 [120.93]

In classroom D3-2, two duplicate IEM units (2A and 2B) have been installed for quality control.

TABLE F.5: *Temperature, Relative Humidity and CO₂ Mean [SD] in Dunedin Schools (Part 2)*

School_id	Room_id	Season	Temperature (°C)	Relative humidity (%)	Carbon dioxide (ppm)
D3	1	Spring	19.28 [2.09]	49.38 [3.18]	1038.52 [359.46]
		Summer	23.96 [2.25]	58.96 [3.29]	1214.48 [488.54]
		Autumn	NA	NA	NA
		Winter	19.86 [1.43]	52.48 [3.50]	1424.24 [364.40]
D3	2A	Spring	21.03 [1.87]	40.67 [5.42]	963.13 [363.10]
		Summer	23.78 [1.65]	57.48 [4.12]	817.38 [287.22]
		Autumn	20.75 [0.44]	56.94 [1.76]	1049.28 [483.56]
		Winter	22.81 [2.22]	41.94 [4.79]	1018.69 [417.90]
D3	2B	Spring	21.14 [1.86]	41.21 [5.18]	939.36 [349.99]
		Summer	23.88 [1.68]	57.71 [4.16]	821.52 [287.41]
		Autumn	20.81 [0.44]	56.74 [1.74]	1039.66 [479.17]
		Winter	22.86 [2.21]	42.14 [4.25]	1011.4 [405.77]
D3	3	Spring	20.12 [1.92]	46.52 [2.84]	1183.25 [385.48]
		Summer	23.21 [1.88]	57.66 [2.18]	831.91 [209.58]
		Autumn	18.7 [0.10]	62.45 [1.17]	1187.52 [256.14]
		Winter	20.19 [1.44]	50.95 [3.34]	1443.97 [336.37]
D3	4	Spring	20.86 [1.59]	41.7 [3.97]	911.61 [339.97]
		Summer	24.55 [1.73]	56.15 [3.38]	880.69 [266.75]
		Autumn	22.03 [0.42]	58.93 [2.12]	1475.65 [505.71]
		Winter	21.65 [1.75]	45.86 [3.86]	1076.4 [382.55]
D4	1	Spring	17.43 [2.10]	45.89 [4.25]	1193.34 [383.06]
		Summer	NA	NA	NA
		Autumn	18.69 [0.99]	65.72 [0.03]	1819 [246.07]
		Winter	19.35 [2.00]	48.33 [4.88]	1099.63 [548.52]

F.3.1 Temperature

Classrooms at risk

- D1-2: Performs poorly in Spring and Summer.
- D2-1: Struggles in Summer and Winter.
- D2-2: Performs poorly across all seasons except Autumn.
- D3-1: Performs poorly in Spring and Summer, with significant temperature issues.
- D3-2A and D3-2B: Struggle in Summer and Winter, with considerable temperature fluctuations.

- D4-1: Performs poorly across all seasons, with significant temperature issues, especially in Spring.

Classrooms performing better

- D1-1: Meets criteria in all seasons except Summer.
- D1-3A and D1-3B: Perform well in Spring and Autumn, with only Summer being problematic.
- D2-4: Performs relatively well across all seasons, with only Summer not meeting criteria.
- D3-3: Performs relatively well, with only minor issues in Spring and Summer.
- D3-4: Performs well in Spring, Autumn, and Winter, with only Summer being problematic.

Seasonal trends

- Summer: All classrooms struggle to meet criteria due to temperatures above 24 °C. This is the most problematic season overall.
- Autumn: All classrooms meet the criteria, making it the best-performing season.
- Spring: Most classrooms perform well, with only minor issues in some rooms (e.g., D1-2, D2-2).
- Winter: Performance varies, with some classrooms meeting criteria (D1-1, D1-2) and others struggling (D2-1, D2-2).
- Summer: All classrooms struggle to meet criteria due to temperatures above 24 °C. This remains the most problematic season overall.
- Autumn: Most classrooms meet criteria or perform well, making it the best-performing season.
- Spring: Performance varies, with some classrooms nearly meeting criteria (D3-2A, D3-2B, D3-4) and others struggling (D3-1, D4-1).
- Winter: Performance is mixed, with some classrooms nearly meeting criteria (D3-1, D3-3, D3-4) and others struggling (D3-2A, D3-2B, D4-1).

F.3.2 Relative humidity

Classrooms at risk

- Classroom D2-1: Shows significant issues in Spring (83% below optimal RH) and Winter (38% below optimal RH).
- Classroom D2-2: Has major problems in Spring (81% below optimal RH) and Winter (45% below optimal RH).
- Classroom D1-4: Performs poorly in Winter (74% below optimal RH) and has issues in Summer (41% above optimal RH).
- Classroom D3-2A and D3-2B: Both show significant issues in Spring (about 50% below optimal RH) and Winter (33-36% below optimal RH).
- Classroom D3-4: Has problems in Spring (35% below optimal RH) and autumn (41% above optimal RH).

Classrooms performing better

- Classroom D1-2: Maintains optimal RH levels for most of the year, with only minor issues in Spring and Winter.
- Classroom D1-3A and D1-3B: Show optimal performance in Summer and Autumn, with only minor issues in Spring.
- Classroom D1-1: Performs well overall, with some issues in Winter (26% below optimal RH).
- Classroom D3-1: Performs well overall, with only minor issues in Summer (50% slightly above optimal RH).
- Classroom D3-3: Maintains good RH levels throughout the year, with only minor issues in Autumn (slightly above optimal RH).
- Classroom D4-1: Shows good performance in the seasons where data is available, with only minor issues in Spring and Winter.

Seasonal trends

- Spring: Most classrooms experience some level of low RH, with D2-1 and D2-2 being the worst affected.
- Summer: Generally good performance across all classrooms, with only D1-4 and D2-4 showing some above-optimal RH levels.
- Autumn: Excellent performance in most classrooms, with only D2-1 and D2-4 showing slightly above-optimal RH levels.
- Winter: The most problematic season for many classrooms, with low RH being a common issue. D1-4, D2-1, and D2-2 are particularly affected.
- Spring: Most classrooms maintain optimal RH levels, with D3-2A, D3-2B, and D3-4 being exceptions (showing below optimal RH).
- Summer: Generally good performance across all classrooms, with some showing slightly above-optimal RH levels (D3-1, D3-2A, D3-2B, D3-3, D3-4).
- Autumn: Excellent performance in most classrooms, with only D3-3 and D3-4 showing above-optimal RH levels.
- Winter: Good performance overall, with D3-2A and D3-2B showing the most significant issues (33-36% below optimal RH).

F.3.3 Carbon dioxide

Classrooms at risk

1. D2-4: Autumn shows 100% of time above 1500 ppm, poor performance in other seasons too.
2. D3-1: Winter shows 50% of time above 1500 ppm, poor Summer performance as well.
3. D2-1: Autumn shows 67% of time above 1500 ppm, poor Winter performance too.
4. D3-3: Winter shows 48% of time above 1500 ppm, generally poor performance across seasons.
5. D1-2: Spring shows 29% of time above 1500 ppm, inconsistent across seasons.

Classrooms performing well

1. D1-3A and D1-3B: Consistently good performance across seasons, rarely exceeding 1000 ppm.
2. D2-2: Generally good performance, with only Winter showing some concern.
3. D3-2A and D3-2B: Relatively consistent performance, with most seasons showing the majority of time below 1000 ppm.

Seasonal trends

1. Summer: Generally the best performing season across most classrooms, with CO₂ levels often below 1000 ppm.
2. Winter: Often the worst performing season, with many classrooms showing high percentages of time above 1500 ppm.
3. Spring and Autumn: Variable performance, but generally worse than Summer and better than Winter.
4. Some classrooms (e.g., D2-4, D2-1) show extreme seasonal variability, suggesting potential issues with ventilation systems or occupancy patterns.

Appendix G

IEM reporting - post COVID-19

This appendix presents the indoor environmental monitoring analysis supporting specific sections of the main text. The following correlations are established:

- **Section G.1** provides IEM data for Chapter 5, **Section 5.4.2** Auckland (August 2022 through June 2024).

G.1 Auckland

G.1.1 Temperature

The WHO advises that when classrooms are occupied during school hours, the temperature should be maintained between 18 °C to 24 °C.

During the winter season, temperature readings generally fall below 18 °C across most classrooms. However, there are a few notable exceptions. In Winter 2024, S1-3 maintains a slightly higher temperature of 18.2 °C, while S1-4 stands out with a significantly warmer reading of 22.5 °C. Interestingly, S1-6, during the same period, remained within the acceptable range, registering a comfortable 23.7 °C. These variations in temperature across different rooms during the winter months highlight the importance of individual climate control and insulation factors within each space.

As spring arrives, temperatures generally remain below 18 °C in most areas. However, there are a few notable exceptions during the Spring 2023 season. S1-1 experiences a slightly warmer temperature of 18.2 °C, while S1-3 closely follows with a reading of 18.2 °C. Additionally, S1-5 barely exceeds the 18 °C threshold, recording a temperature of 18.5 °C. These minor variations above the general trend suggest

that certain rooms may have unique factors influencing their temperature, such as sun exposure, insulation, or specific heating arrangements. Despite these exceptions, the overall pattern indicates that spring temperatures tend to stay on the cooler side in most locations.

During the summer months, temperatures generally maintain a comfortable range between 18 °C and 24 °C in most areas. This trend indicates a generally well-regulated environment during the warmer season. However, there are two notable exceptions where temperatures exceed the upper limit of this range. In Summer 2024, S1-4 experienced a significantly higher temperature of 27.8 °C, while S1-6 stands out with an even warmer reading of 29.7 °C. These elevated temperatures in specific rooms during the peak of summer suggest potential issues with cooling systems, increased sun exposure, or other factors contributing to localized heat buildup. Such exceptions highlight the importance of targeted climate control measures in these particular areas to ensure comfort during the hottest parts of the year.

Autumn temperatures generally fall within the recommended range, providing comfortable conditions in most areas during this transitional season. However, there are a few notable exceptions that deviate from this pattern. In Autumn 2023, S1-1 experienced a slightly cooler temperature of 17.5 °C, just below the recommended threshold. Conversely, during Autumn 2024, two rooms exceed the upper limit of the range. S1-2 registers a temperature of 24.8 °C, which is marginally above the recommended maximum, while S1-6 shows a more significant elevation at 26.7 °C. These variations highlight the challenges of maintaining consistent temperatures across different spaces during a season characterized by fluctuating weather conditions. Such exceptions may warrant closer attention to heating and cooling systems in these specific rooms to ensure optimal comfort throughout the autumn months.

G.1.2 Relative humidity

The assessment of classroom comfort is based on guidelines established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). ASHRAE recommends maintaining RH levels between 40% and 60% when temperatures are within the 18 °C to 24 °C range for optimal comfort. It is

worth noting that these standards remained unchanged following the COVID-19 pandemic.

The analysis of various rooms reveals diverse compliance patterns with specified criteria across different seasons. S1-1 meets the Winter 2022 and Autumn 2024 requirements while exceeding the upper limit for all other seasons. S1-2 only meets the criteria for Winter 2022, with all other seasons surpassing the upper limit. S1-3 demonstrates compliance for Winter 2022, Winter 2023, and Autumn 2024 but exceeds the limit for the remaining seasons.

S1-4 and S1-6 stand out as they meet the criteria for all seasons, specifically Summer 2024, Autumn 2024, and Winter 2024. S1-5 shows a mixed pattern, meeting the Spring 2023, Summer 2024, and Autumn 2024 requirements while slightly exceeding the upper limit for Winter 2024. This varied performance across rooms and seasons suggests potential differences in environmental control, occupancy patterns, or other influential factors affecting each space.

Compliance analysis:

- Mostly compliant room: S1-4, S1-5 and S1-6
- Partially compliant rooms: S1-1, S1-2, and S1-3

To fully meet the ASHRAE criteria:

1. S1-1, S1-2, and S1-3 would require dehumidification, especially during spring and summer.
2. S1-5 might benefit from slight dehumidification in winter.
3. S1-4 and S1-6 already meet the criteria and should maintain their current conditions.

G.1.3 Carbon dioxide

Data on the percentage of time that classrooms in the Auckland school maintain CO₂ concentrations in Auckland classrooms within specific ranges across different seasons is presented in Chapter 6.

Classroom performance (pre-COVID-19)

1. S1-1:

- Winter 2022 to Autumn 2023: CO₂ levels are consistently below 800 ppm (100% compliance), indicating no issues with the guidelines.
- Winter 2023 to Winter 2024: Slight deviations with CO₂ levels 98% below 800 ppm, 1% between 800 and 1000 ppm, and 1% between 1000 and 1500 ppm. This still meets the MoE guideline since the daily average will likely remain well below 1200 ppm, and levels never exceed 1500 ppm.

2. S1-2:

- Winter 2022 to Autumn 2023: Consistently maintains CO₂ levels below 800 ppm, indicating no issues.
- Winter 2023 to Winter 2024: Similar to S1-1, with 98% of time below 800 ppm and 1% in both the 800-1000 ppm and 1000-1500 ppm ranges. This room meets the guidelines.

3. S1-3:

- Winter 2022 to Autumn 2023: 100% compliance with CO₂ levels below 800 ppm.
- Winter 2023 to Winter 2024: Shows 98% compliance with minor deviations (1% each in 800-1000 ppm and 1000-1500 ppm ranges). CO₂ levels remain within acceptable limits.

4. S1-4:

- Summer 2024: High compliance with 99% below 800 ppm and 1% in the 800-1000 ppm range.
- Autumn 2024: Shows 95% below 800 ppm, 3% in the 800-1000 ppm range, and 2% up to 1500-2000 ppm. In Winter 2024: This room exhibits more significant deviations, with 86% below 800 ppm, 4% in the 800-1000 ppm range, 7% in the 1000-1500 ppm range, and 2% between 1500 and 2000 ppm. While it is usually within acceptable limits, the presence of higher levels suggests a need for improved ventilation.

5. S1-5:

- Summer 2024 to Winter 2024: 100% compliance with CO₂ levels below 800 ppm, indicating optimal ventilation and air quality management.

6. S1-6:

- Summer 2024: Maintains 99% of CO₂ levels below 800 ppm, with 1% in the 1000-1500 ppm level.
- Autumn 2024: Compliance drops to 92% below 800 ppm, 3% in the 800-1000 ppm range, 4% in 1000-1500, and 1% up to 1500-2000.
- Winter 2024: Shows 90% below 800 ppm, 4% in the 800-1000 range, 4% in 1000-1500, and 3% up to 2000 ppm, indicating a need for action during these periods.

Classroom performance (post-COVID-19)

1. S1-1:

- Winter 2022 to Spring 2023 Seasons: Consistently maintains CO₂ levels below 800 ppm with 100% compliance.
- Summer 2024 to Winter 2024 Seasons: Shows minor deviations with 98% of time below 800 ppm and 1% in the 800-1250 and 1250-2000 ppm ranges, indicating brief increases above the recommended threshold.

2. S1-2:

- Winter 2022 to Spring 2023 Seasons: Similar to S1-1 with 100% compliance (CO₂ levels below 800 ppm).
- Summer 2024 to Winter 2024 Seasons: Minimal deviation with 98% compliance and 1% of time in both the 800-1250 and 1250-2000 ppm ranges.

3. S1-3:

- Winter 2022 to Spring 2023 Seasons: 100% compliance.
- Summer 2024 to Winter 2024 Seasons: Similar pattern with 98% compliance and minor increase up to 1% in the 800-1250 and 1250-2000 ppm ranges.

4. S1-4:

- Autumn 2024: Moderate compliance with 95% below 800 ppm and increases of 3% and 2% in the 800-1250 and 1250-2000 ppm ranges, respectively.
- Winter 2024: Lower compliance with 86% below 800 ppm, showing significant levels above the threshold: 4% in the 800-1250 range and 9% in the 1250-2000 range.

5. S1-5:

- Summer 2024 to Winter 2024: Perfect compliance with 100% of CO₂ levels maintained below 800 ppm.

6. S1-6:

- Summer 2024: High compliance with 99% below 800 ppm and a minor deviation of 1% in the 800 -1250 range.
- Autumn 2024: Somewhat lower compliance with 92% of CO₂ levels maintained below 800 ppm, and notable deviations: 7% in the 800-1250 range and 1% in the 1250-2000 range.
- Winter 2024: Further decrease in compliance with 90% below 800 ppm, and considerable deviations: 8% in the 800-1250 range and 2% in the 1250-2000 range.

Appendix H

Cognitive test results

This appendix presents the cognitive test analysis supporting specific sections of the main text. The following correlations are established:

- **Section H.1** corresponds to the analysis in Chapter 7, **Section 7.2.2**
- **Section H.2** corresponds to the analysis in Chapter 7, **Section 7.2.3**
- **Section H.3** underpins the findings discussed in Chapter 7, **Section 7.2.4**
- **Section H.4 and H.5** corresponds to the ANOVA analysis in Chapter 7, **Section 7.2.5**
- **Section H.6** corresponds to the analysis in Chapter 7, **Section 7.3**

H.1 Environmental conditions in classrooms

TABLE H.1: *Mean [SD] of Environmental & Metabolic Parameters for Test Protocols*

Date	Room	Test	Temp (°C)	RH (%)	CO ₂ (ppm)
19/3	6 am	1	24.8 [0.14]	44 [3.50]	523 [45.16]
	6 pm	3	24.6 [2.72]	39 [1.21]	1134 [242.06]
22/3	5 am	1	23.1 [1.54]	60 [14.16]	532 [84.72]
	7 am	1	20.8 [0.12]	58 [0.55]	538 [32.69]
	7 pm	1	22.3 [0.03]	54 [0.27]	475 [13.05]
4/4	5 am	2	26.1 [0.45]	48 [7.71]	823 [100.87]
	6 am	2	23.1 [1.55]	60 [14.17]	532 [84.72]
8/4	5 am	1	22.1 [2.55]	57 [5.89]	531 [95.38]
	5 am	3	25.2 [0.18]	57 [2.35]	1165 [145.59]
	7 pm	1	22.3 [0.06]	55 [0.52]	575 [7.87]
	7 am	2	22.1 [0.02]	57 [0.05]	724 [2.55]
29/5	7 pm	3	22.9 [0.29]	51 [1.15]	1476 [26.95]
30/5	6 am	2	25.6 [0.02]	46 [0.34]	829 [13.31]
5/6	6 am	3	25.7 [1.77]	49 [3.99]	1072 [119.65]
11/6	6 pm	1	23.3 [0.03]	48 [0.29]	578 [10.82]
12/6	5 am	2	22.8 [0.19]	51 [0.95]	917 [36.10]
	5 pm	2	22.2 [0.14]	50 [0.09]	846 [73.80]
18/6	6 pm	2	24.6 [2.23]	51 [8.29]	757 [21.94]
21/6	5 pm	3	22.8 [0.36]	55 [0.73]	1207 [78.91]
25/6	6 pm	2	26.7 [0.10]	46 [0.10]	944 [27.03]
26/6	5pm	1	19.6 [0.10]	57 [0.00]	710 [7.00]
	7pm	2	20.6 [0.15]	52 [0.29]	647 [17.73]

H.2 Homogeneity of variance - Levene's Test

Section H.1 corresponds to the analysis in Chapter 7, section 7.2.3

TABLE H.2: *Levene's Test for Homogeneity of Variance Results by Classroom and Test Condition*

DOUBLE TROUBLE				SPATIAL PLANNING			
Room	Df	F value	Pr(>F)	Room	Df	F value	Pr(>F)
1	2 (105)	1.418	0.247	1	2 (105)	0.329	0.720
2	2 (131)	0.032	0.969	2	2 (134)	2.398	0.095
3	2 (95)	0.297	0.744	3	2 (101)	0.477	0.622

SPATIAL SPAN				ODD ONE OUT			
Room	Df	F value	Pr(>F)	Room	Df	F value	Pr(>F)
1	2 (101)	1.000	0.372	1	2 (95)	0.435	0.649
2	2 (127)	0.382	0.684	2	2 (124)	4.604	0.012
3	2 (99)	1.222	0.299	3	2 (85)	1.957	0.148

H.2.1 Double Trouble results

- For all three rooms, the p -values ($\text{Pr}(>F)$) exceed the typical significance level of 0.05. This indicates that the null hypothesis of Levene's test, which claims equal variances across groups, cannot be rejected for all three rooms.
- This suggests that the variances of the dependent variable are not significantly different across the three conditions (Test 1, Test 2, Test 3) in any of the rooms.
- This result is somewhat surprising given the different environmental conditions described earlier. It suggests that despite the attempts to create different environments, these differences did not lead to significantly different variances in the measured outcome.
- S1-2 shows the most homogeneous variances ($F = 0.032$, $p = 0.969$), while S1-1 shows the least (though still not significantly different) homogeneity ($F = 1.418$, $p = 0.247$).

H.2.2 Spatial Planning results

- For all three rooms, the p -values ($\text{Pr}(>F)$) exceed the typical significance level of 0.05. This indicates a failure to reject the null hypothesis of Levene's test for all

three rooms, suggesting that the variances are not significantly different across the three conditions.

- These results are consistent with those from the previous cognitive test (DT), suggesting that the environmental manipulations did not significantly affect the variability of performance on either cognitive task.
- The consistency across both cognitive tests (DT and SP) strengthens the conclusion that the different environmental conditions did not lead to significantly different variances in cognitive performance.

H.2.3 Spatial Span results

- For all three rooms, the p -values ($\Pr(>F)$) are greater than the typical significance level of 0.05. This means that the variances of the SS test scores are not significantly different across the three environmental conditions.
- These findings are consistent with the results from the previous two cognitive tests.
- S1-3 shows the lowest p -value (0.299), but it is still well above the conventional significance level of 0.05.

H.2.4 Odd One Out results

- S1-1 and S1-3:
 - For these rooms, the p -values are greater than 0.05 (0.649 and 0.148, respectively).
 - This indicates a failure to reject the null hypothesis of Levene's test for S1-1 and S1-3, suggesting no significant differences in variances across the three environmental conditions.
- S1-2:
 - The p -value is 0.012, which is less than the typical significance level of 0.05.
 - This implies the rejection of the null hypothesis of Levene's test for S1-2.
 - This suggests that in S1-2, there are significant differences in the variances of the OOO test scores across the three environmental conditions.

H.3 Test for Normality - Shapiro-Wilk test

Section H.2 underpins the findings discussed in Chapter 7, section 7.2.4

Table H.3 and **Table H.4** provide a detailed analysis of the Shapiro-Wilk test for normality.

TABLE H.3: *Shapiro-Wilk Test for Normality Results by Classroom and Test Condition*

DOUBLE TROUBLE	SPATIAL PLANNING
Shapiro-Wilk test results for EnvironType TEST 1 and Room RM5 n = 42 p -value = 0.022 Interpretation The data is not normally distributed	Shapiro-Wilk test results for EnvironType TEST 1 and Room RM5 n = 41 p -value = 0.174 Interpretation The data is normally distributed .
TEST 1 and Room RM6 n = 30 p -value = 0.009 Interpretation The data is not normally distributed	TEST 1 and Room RM6 n = 33 p -value = 0.286 Interpretation The data is normally distributed .
TEST 1 and Room RM7 n = 52 p -value = 0.009 Interpretation The data is not normally distributed	TEST 1 and Room RM7 n = 54 p -value = 0.000 Interpretation The data is not normally distributed
TEST 2 and Room RM5 n = 41 p -value = 0.051 Interpretation The data is normally distributed .	TEST 2 and Room RM5 n = 42 p -value = 0.915 Interpretation The data is normally distributed .
TEST 2 and Room RM6 n = 72 p -value = 0.004 Interpretation The data is not normally distributed	TEST 2 and Room RM6 n = 69 p -value = 0.178 Interpretation The data is normally distributed .
TEST 2 and Room RM7 n = 30 p -value = 0.043 Interpretation The data is not normally distributed	TEST 2 and Room RM7 n = 32 p -value = 0.402 Interpretation The data is normally distributed .
TEST 3 and Room RM5 n = 25 p -value = 0.150 Interpretation The data is normally distributed .	TEST 3 and Room RM5 n = 25 p -value = 0.937 Interpretation The data is normally distributed .
TEST 3 and Room RM6 n = 32 p -value = 0.149 Interpretation The data is normally distributed .	TEST 3 and Room RM6 n = 35 p -value = 0.191 Interpretation The data is normally distributed .
TEST 3 and Room RM7 n = 16 p -value = 0.107 Interpretation The data is normally distributed .	TEST 3 and Room RM7 n = 18 p -value = 0.187 Interpretation The data is normally distributed .

TABLE H.4: *Shapiro-Wilk Test for Normality Results by Classroom and Test Condition continued*

SPATIAL SPAN	ODD ONE OUT
Shapiro-Wilk test results for EnvironType	
TEST 1 and Room RM5	TEST 1 and Room RM5
n = 39 p -value = 0	n = 37 p -value = 0.078
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 1 and Room RM6	TEST 1 and Room RM6
n = 32 p -value = 0.000	n = 32 p -value = 0.625
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 1 and Room RM7	TEST 1 and Room RM7
n = 54 p -value = 0.000	n = 46 p -value = 0.564
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 2 and Room RM5	TEST 2 and Room RM5
n = 40 p -value = 0.000	n = 38 p -value = 0.121
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 2 and Room RM6	TEST 2 and Room RM6
n = 65 p -value = 0.000	n = 64 p -value = 0.462
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 2 and Room RM7	TEST 2 and Room RM7
n = 30 p -value = 0.01	n = 27 p -value = 0.302
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 3 and Room RM5	TEST 3 and Room RM5
n = 25 p -value = 0.018	n = 23 p -value = 0.941
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 3 and Room RM6	TEST 3 and Room RM6
n = 33 p -value = 0.002	n = 31 p -value = 0.771
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.
TEST 3 and Room RM7	TEST 3 and Room RM7
n = 18 p -value = 0.013	n = 15 p -value = 0.544
Interpretation The data is not normally distributed	Interpretation The data is normally distributed.

H.3.1 Results for S1-1

Observations:

1. SS consistently shows non-normal distribution across all conditions.
2. Test 1 condition shows mixed results, with two tests indicating non-normality.

3. Test 2 condition (marginally elevated warmth) shows mostly normal distributions, except for SS.
4. Test 3 condition (elevated CO₂ and temperature) shows the most consistent normality across tests, except for SS.

H.3.2 Results for S1-2

Observations:

1. The SS test consistently showed significant effects across all conditions, suggesting it might be the most sensitive to environmental changes.
2. DT test showed significant effects in Test 1 (T1) and Test 2 (T2) conditions but not in Test 3 (T3) conditions.
3. OOO and SP tests did not show significant effects in any condition, indicating they might be less affected by these environmental factors.
4. The T3 condition (elevated CO₂ and temperature with face masks) seemed to have the least impact on cognitive performance, with only SS showing significance.
5. The T2 condition (marginally elevated warmth) showed similar patterns to the Test 1 condition, suggesting slight temperature increases might not drastically alter cognitive performance.

H.3.3 Results for S1-3

Observations:

1. The T1 condition showed the most significant effects across tests, with three out of four tests showing statistical significance.
2. SS test consistently showed significant effects across all conditions, similar to S1-2.
3. DT test showed significant effects in T1 and T2 conditions but not in T3 condition, again similar to S1-2.
4. Unlike S1-2, SP showed a highly significant effect in the T1 condition but not in other conditions.

5. OOO test did not show significant effects in any condition, consistent with S1-2.
6. The T3 condition had the least impact on cognitive performance, with only SS showing significance, similar to S1-2.
7. The sample sizes (n) for the T3 condition are notably smaller compared to other conditions, which might affect the reliability of these results.

Comparison with S1-2:

- Both rooms show consistent effects for SS across all conditions.
- Both rooms show significant effects for DT in T1 and T2 conditions.
- S1-3 shows a strong effect for SP in the T1 condition, which was not observed in S1-2.
- The T3 condition seems to have the least impact on cognitive performance in both rooms.

H.4 ANOVA results

Section H.3 and H.4 correspond to the ANOVA analysis in Chapter 7, section 7.2.5

H.4.1 Within class ANOVA

A within-classroom ANOVA has been performed between the three classrooms.

Double Trouble

1. **T1 conditions:** S1-1 shows the highest variability, suggesting that natural ventilation had a more varied effect on students in this room. S1-3 shows the least variability, indicating more consistent performance under these conditions.
 2. **T2 conditions:** S1-1 and S1-3 show similar high variability, suggesting that marginally elevated warmth had a more varied effect on performance in these rooms. S1-2 consistently shows the least variability across all test conditions.
 3. **T3 conditions:** S1-3 shows the highest variability, suggesting that elevated CO₂ and temperature might have had a more varied effect on performance in this room. S1-2 shows the least variability, indicating more consistent performance despite the challenging conditions.
- **Overall observations:**
 - S1-2 consistently shows the lowest variability across all test conditions, suggesting that environmental changes might affect students in this room less.
 - The T3 environment (elevated CO₂ and temperature) generally shows lower variability compared to the T1 environment, except for S1-3. This could indicate that the more controlled environment led to more consistent performance, possibly due to increased focus or alertness.
 - The T2 environment (marginally elevated warmth) shows mixed effects, with high variability in S1-1 and S1-3 but low variability in S1-2.

Spatial Planning

1. **T1 conditions:** S1-1 shows the highest variability, suggesting that natural ventilation might have had a more varied effect on SP performance in this room.

S1-3 shows the least variability, indicating more consistent performance under these conditions.

2. **T2 conditions:** S1-1 again shows the highest variability, suggesting that marginally elevated warmth had a more varied effect on performance in this room. S1-3 shows the least variability, indicating more consistent performance under these conditions.
3. **T3 conditions:** S1-1 again shows the highest variability, suggesting that elevated CO₂ and temperature might have had a more varied effect on performance in this room. S1-2 shows the least variability, indicating more consistent performance despite the challenging conditions.

- **Overall observations:**

- S1-1 consistently shows the highest variability across all test conditions for the SP test. This suggests that students in S1-1 might be more sensitive to environmental changes when performing SP tasks.
- S1-3 shows the lowest variability in both T1 and T2 conditions, indicating more consistent performance in these environments.
- The T3 environment generally shows lower variability compared to the T1 environment in S1-2 and S1-3, but not in S1-1.

- **Comparisons with Other Tests:**

- The patterns of variability for "SP" are different from those observed for "DT" and "OOO," suggesting that different cognitive tasks may be affected differently by environmental conditions.
- The overall variability (as indicated by mean square values) is generally higher for "SP" compared to "OOO," which might suggest that performance on this test is more sensitive to environmental variations.

Spatial Span

1. **T1 conditions:** In S1-2, the T1 condition shows the highest variance.
2. **T2 conditions:** In S1-1, the T2 condition shows the highest variance.
3. **T3 conditions:** In S1-3, the T2 condition shows the highest variance.

Odd One Out

1. **T1 conditions:** S1-2 shows the highest variability, suggesting that natural ventilation might have had a more varied effect on "OOO" performance in this room. S1-3 shows the least variability, indicating more consistent performance under these conditions.
2. **T2 conditions:** S1-3 shows the highest variability, suggesting that marginally elevated warmth had a more varied effect on performance in this room. S1-1 shows the least variability, indicating more consistent performance under these conditions.
3. **T3 conditions:** S1-1 shows the highest variability, suggesting that elevated CO₂ and temperature might have had a more varied effect on performance in this room. S1-3 shows the least variability, indicating more consistent performance despite the challenging conditions.

- **Overall observations:**

- The T3 environment generally shows lower variability compared to the T1 environment, especially in S1-2 and S1-3. This could indicate that the more controlled environment led to a more consistent performance on the "OOO" test.
- S1-3 shows interesting patterns: it has the lowest variability in T1 conditions, the highest in T2 conditions, and the lowest again in T3 conditions.
- S1-2 shows high variability in T1 conditions but becomes more consistent in T3 and T2 conditions.

- **Comparisons with "Double Trouble" Test:**

- The patterns of variability for "OOO" are different from those observed for "DT," suggesting that different cognitive tests may be affected differently by environmental conditions.
- The overall variability (as indicated by mean square values) is generally lower for "OOO" compared to "DT," which might suggest that performance on this test is less sensitive to environmental variations.

H.4.2 Between-class ANOVA

A between-classroom ANOVA has been performed between the three classrooms.

Test 1 condition (Normal environment)

Based on the results provided the following can be inferred:

1. DT

- There is a statistically significant difference between rooms ($F(2, 121) = 6.589, p = 0.001$).
- The effect is significant at the 0.01 level.
- This suggests that the room conditions have a notable impact on performance in the DT test under normal conditions.

2. SP

- There is a marginally significant difference between rooms ($F(2, 125) = 2.512, p = 0.085$).
- The effect is significant at the 0.1 level.
- This suggests a weak relationship between room conditions and performance in the SP test under normal conditions.

3. SS

- There is no statistically significant difference between rooms ($F(2, 122) = 1.645, p = 0.197$).
- This implies that room conditions do not significantly affect performance in the SS test under normal conditions.

4. OOO

- There is a highly statistically significant difference between rooms ($F(2, 112) = 8.69, p = 0.0003$).
- The effect is significant at the 0.001 level.
- This indicates a strong relationship between room conditions and performance in the OOO test under normal conditions.

Overall, these results suggest that under normal classroom conditions:

- Room conditions have a significant impact on performance in DT and OOO tests.
- There's a weak relationship between room conditions and SP performance.
- Room conditions do not significantly affect SS performance.

These findings could indicate that different cognitive tasks are affected differently by classroom environmental conditions, even under normal circumstances. The impact seems strongest for tasks involving cognitive flexibility (DT) and visual reasoning (OOO), less pronounced for planning tasks (SP), and negligible for working memory tasks (SS).

Test 2 condition (Marginally elevated warmth condition)

1. DT

- $F(2, 140) = 0.785, p = 0.458$
- There is no statistically significant difference between rooms.

2. OOO

- $F(2, 126) = 0.14, p = 0.869$
- There is no statistically significant difference between rooms.

3. SP

- $F(2, 140) = 1.437, p = 0.241$
- There is no statistically significant difference between rooms.

4. SS

- $F(2, 132) = 0.824, p = 0.441$
- There is no statistically significant difference between rooms.

Key inferences:

- **Uniform impact:** Under the T2 condition (marginally elevated warmth), no statistically significant differences in performance across rooms exist for any of the four cognitive tests.

- **Contrast with T1 condition:** This notably differs from the T1 condition results, where significant differences were observed for some tests (particularly DT and OOO).
- **Potential equalizing effect:** The marginally elevated warmth condition might equalise performance across different rooms, possibly by overriding or masking the influential room-specific factors under normal conditions.
- **Consistent non-significance:** The consistently non-significant results across all four tests suggest that the T2 condition affects cognitive performance similarly across different rooms and cognitive tasks.
- **Possible adaptation:** Students might be adapting to the slightly warmer conditions in a way that negates room-specific differences that were present under normal conditions.
- **Task independence:** Under T2 conditions, performance on different cognitive tasks (involving various cognitive processes like cognitive flexibility, visual reasoning, planning, and working memory) seems to be similarly unaffected by room differences.
- **Research implications:** These results suggest that the impact of room conditions on cognitive performance might be temperature-dependent, with slightly elevated temperatures potentially neutralizing room-specific effects observed under normal conditions.

It is important to note that while these results show no significant differences between rooms under T2 conditions, they do not necessarily indicate whether overall performance has improved or declined compared to the T1 condition. Further analysis comparing performance across conditions would be needed to determine the overall impact of the marginally elevated warmth on cognitive performance.

Test 3 condition (Elevated CO₂ and temperature condition)

Based on the results provided for the T3 (Elevated CO₂ and temperature condition) scenario, we can infer the following:

1. DT

- $F(2, 70) = 7.27, p = 0.001$

- There is a highly significant difference between rooms (significant at the 0.01 level).
- This suggests that room conditions strongly impact performance in the DT test under elevated CO₂ and temperature conditions.

2. OOO

- $F(2, 66) = 3.349, p = 0.041$
- There is a significant difference between rooms (significant at the 0.05 level).
- This indicates that room conditions affect performance in the OOO test under these conditions, though less strongly than for DT.

3. SP

- $F(2, 75) = 3.897, p = 0.024$
- There is a significant difference between rooms (significant at the 0.05 level).
- This suggests that room conditions impact performance in the SP test under elevated CO₂ and temperature conditions.

4. SS

- $F(2, 73) = 0.294, p = 0.746$
- There is no statistically significant difference between rooms.
- This implies that room conditions do not significantly affect performance in the SS test under these conditions.

Key inferences:

- **Differential impact:** Under T3 conditions, different cognitive tasks are affected to varying degrees by room conditions.
- **Strongest effect on cognitive flexibility:** The DT test shows the strongest room-related differences.
- **Moderate effects on visual reasoning and planning:** Both OOO (visual reasoning) and SP tests show significant, but less pronounced, room-related differences.

- **No effect on working memory:** The SS test shows no significant room-related differences.
- **Comparison with other conditions:** Unlike the T2 condition, where no significant differences were found, the T3 condition shows significant room-related effects for most tests. The pattern is similar to the T1 condition but has stronger effects, particularly for SP.
- **Potential CO₂ and temperature sensitivity:** The significant differences observed under T3 conditions suggest that elevated CO₂ levels and temperature may amplify the impact of room-specific factors on cognitive performance.
- **Task-specific vulnerability:** Different cognitive processes appear to have varying levels of vulnerability to the combined effects of room conditions, elevated CO₂, and temperature.
- **Research implications:** These results highlight the importance of considering both environmental conditions (CO₂, temperature) and room-specific factors when assessing cognitive performance in educational settings.

These findings suggest that under elevated CO₂ and temperature conditions, room-specific factors become more influential in determining cognitive performance, particularly for tasks involving cognitive flexibility, visual reasoning, and planning. The consistent lack of effect on the SS task across all conditions is noteworthy and may indicate that working memory is more resilient to these environmental variations.

Of the results presented, five do not meet the established significance threshold ($p > 0.005$). Tukey's HSD posthoc test was conducted to identify specific group differences.

H.4.3 Tukey's HSD posthoc test results

T1 and DT

Tukey's HSD (Honestly Significant Difference) post-hoc test was conducted to compare multiple means with a 95% family-wise confidence level for T1 DT with p -value = 0.001. The results are displayed in **Table H.5**.

TABLE H.5: *Tukey's HSD Test Results for T1 DT (95% Confidence Level)*

Room	Diff	Lower	Upper	<i>p</i> adj
S1-2 - S1-1	-11.633	-19.921	-3.345	0.003
S1-3 - S1-1	-8.685	-15.878	-1.492	0.013
S1-3 - S1-2	2.947	-5.001	10.896	0.654

Levene's Test for Homogeneity of variances:

- $p\text{-value} = 0.088 > 0.05$, so we fail to reject the null hypothesis of equal variances

Tukey's HSD posthoc Test: Significant differences found between:

- S1-2 and S1-1 ($p \text{ adj} = 0.003 < 0.01$)
- S1-3 and S1-1 ($p \text{ adj} = 0.013 < 0.05$)

No significant difference between S1-3 and S1-2 ($p \text{ adj} = 0.654 > 0.05$).

Interpretation:

1. There are significant differences in scores between rooms (ANOVA result).
2. The assumption of homogeneity of variances is met (Levene's test).
3. Specifically, S1-2 and S1-3 have significantly lower scores than S1-1, but there's no significant difference between S1-2 and S1-3 (Tukey's HSD test).

The negative differences in the Tukey test indicate that the first room in each comparison (e.g., S1-2 in "2-1") has a lower mean score than the second room (e.g., S1-1).

T1 and OOO

Tukey's HSD posthoc test compared multiple means with a 95% family-wise confidence level for T1 OOO with $p\text{-value} = 0.0003$. The results are displayed in **Table H.6**.

TABLE H.6: *Tukey's HSD Test Results for T1 OOO (95% Confidence Level)*

Room	Diff	Lower	Upper	<i>p</i> adj
S1-2 - S1-1	-2.241	-4.940	0.456	0.123
S1-3 - S1-1	2.250	-0.218	4.718	0.081
S1-3 - S1-2	4.491	1.918	7.065	0.0001

Levene's Test for Homogeneity of Variances:

- $p\text{-value} = 0.126 > 0.05$, so we fail to reject the null hypothesis of equal variances

Tukey's HSD posthoc Test: Significant differences found between:

- S1-3 and S1-2 ($p \text{ adj} = 0.0001 < 0.001$)

No significant difference between S1-2 and S1-1 ($p \text{ adj} = 0.123 > 0.05$) and S1-3 and S1-1 ($p \text{ adj} = 0.081 > 0.05$, but close to significance)

Interpretation:

1. There are significant differences in scores between rooms for the "OOO" task (ANOVA result).
2. The assumption of homogeneity of variances is met (Levene's test).
3. S1-3 has significantly higher scores than S1-2 (difference of 4.491848 points). There's no significant difference between S1-2 and S1-1, although S1-2 tends to have slightly lower scores. The difference between S1-3 and S1-1 is not statistically significant, but it is close ($p = 0.081$). S1-3 tends to have higher scores than S1-1.

In summary, for the "OOO" task, S1-3 performs significantly better than S1-2. While not statistically significant, a trend suggests S1-3 might also perform better than S1-1, and S1-1 might perform better than S1-2. The differences between rooms are more pronounced in this task compared to the "DT" task from the previous analysis.

T3 and DT

Tukey's HSD posthoc test compared multiple means with a 95% family-wise confidence level for T3 DT with $p\text{-value} = 0.001$. The results are displayed in **Table H.7**.

TABLE H.7: *Tukey's HSD Test Results for T3 DT (95% Confidence Level)*

Room	Diff	Lower	Upper	$p \text{ adj}$
S1-2 - S1-1	-13.81	-22.486	-5.133	0.0008
S1-3 - S1-1	-7.31	-17.716	3.096	0.219
S1-3 - S1-2	6.50	-3.452	16.452	0.268

Levene's Test for Homogeneity of Variances:

- $p\text{-value} = 0.995 > 0.05$, so we fail to reject the null hypothesis of equal variances

Tukey's HSD posthoc Test: Significant differences found between:

- S1-2 and S1-1 ($p\text{ adj} = 0.0008 < 0.001$)

No significant difference between S1-3 and S1-1 ($p\text{ adj} = 0.219 > 0.05$) and S1-3 and S1-2 ($p\text{ adj} = 0.268 > 0.05$).

Interpretation:

1. There are significant differences in scores between rooms for the "T3 - DT" task (ANOVA result).
2. S1-2 has significantly lower scores than S1-1 (difference of -13.81 points).
3. There's no statistically significant difference between S1-3 and S1-1, although S1-3 tends to have slightly lower scores. There's no statistically significant difference between S1-3 and S1-2, although S1-3 tends to have slightly higher scores.

In summary, S1-1 performs significantly better than S1-2. S1-3's performance is intermediate between S1-1 and S1-2 but not significantly different from either. The largest and only significant difference is between S1-1 and S1-2. This pattern suggests that for this specific task and group (T3), S1-1 conditions might be more conducive to better performance, especially when compared to S1-2. S1-3 shows intermediate results, not significantly different from either extreme.

T3 and OOO

Tukey's HSD posthoc test compared multiple means with a 95% family-wise confidence level for T3 OOO with $p\text{-value} = 0.041$. The results are displayed in Table H.8.

TABLE H.8: Tukey's HSD Test Results for T1 OOO (95% Confidence Level)

Room	Diff	Lower	Upper	$p\text{ adj}$
S1-2 - S1-1	-1.384	-3.933	1.165	0.399
S1-3 - S1-1	1.727	-1.347	4.802	0.374
S1-3 - S1-2	3.111	0.198	6.025	0.033

Levene's Test for Homogeneity of Variances:

- $p\text{-value} = 0.107 > 0.05$, so we fail to reject the null hypothesis of equal variances

Tukey's HSD posthoc Test: Significant differences found between:

- S1-3 and S1-2 ($p \text{ adj} = 0.033 < 0.05$)

No significant difference between S1-2 and S1-1 ($p \text{ adj} = 0.399 > 0.05$) and S1-3 and S1-1 ($p \text{ adj} = 0.374 > 0.05$).

Interpretation:

1. There are significant differences in scores between rooms for the "T3 - OOO" task (ANOVA result). However, the effect is not as strong as in some previous analyses ($p\text{-value}$ is closer to 0.05).
2. The assumption of homogeneity of variances is met (Levene's test).
3. S1-3 has significantly higher scores than S1-2 (difference of 3.111828 points). There's no statistically significant difference between S1-2 and S1-1, although S1-2 tends to have slightly lower scores. There's no statistically significant difference between S1-3 and S1-1, although S1-3 tends to have slightly higher scores.

In summary, S1-3 performs significantly better than S1-2. S1-1's performance is intermediate between S1-3 and S1-2 but not significantly different from either. The only significant difference is between S1-3 and S1-2. This pattern suggests that for this specific task and group (T3), S1-3 conditions might be more conducive to better performance, especially when compared to S1-2. S1-1 shows intermediate results, not significantly different from either extreme. Interestingly, this pattern somewhat differs from the "T3 - DT" task, where S1-1 performed best. This highlights the importance of considering task-specific effects when evaluating room performance.

T3 and SS

Tukey's HSD posthoc test compared multiple means with a 95% family-wise confidence level for T3 SS with $p\text{-value} = 0.024$. The results are displayed in **Table H.9**.

TABLE H.9: *Tukey's HSD Test Results for T3 SS (95% Confidence Level)*

Room	Diff	Lower	Upper	p adj
S1-2 - S1-1	-5.834	-10.925	-0.742	0.020
S1-3 - S1-1	-2.231	-8.241	3.779	0.649
S1-3 - S1-2	3.603	-2.036	9.242	0.283

Levene's Test for Homogeneity of Variances:

- $p\text{-value} = 0.100 > 0.05$, so we fail to reject the null hypothesis of equal variances

Tukey's HSD posthoc Test: Significant differences found between:

- S1-2 and S1-1 ($p \text{ adj} = 0.020 < 0.05$)

No significant difference between S1-3 and S1-1 ($p \text{ adj} = 0.649 > 0.05$) and S1-3 and S1-2 ($p \text{ adj} = 0.283 > 0.05$).

Interpretation:

1. There are significant differences in scores between rooms for the "T3 - SP" task (ANOVA result).
2. S1-2 has significantly lower scores than S1-1 (difference of -5.834 points).
3. There is no statistically significant difference between S1-3 and S1-1, although S1-3 tends to have slightly lower scores. There's no statistically significant difference between S1-3 and S1-2, although S1-3 tends to have slightly higher scores.

S1-1 performs significantly better than S1-2. S1-3's performance is intermediate between S1-1 and S1-2 but not significantly different from either. The only significant difference is between S1-1 and S1-2. S1-1 conditions might be more conducive to better performance in SP tasks, especially when compared to S1-2. S1-3 shows intermediate results, not significantly different from either extreme. Interestingly, this pattern is similar to what was observed in the "T3 - DT" task, where S1-1 also performed best. This consistency across different tasks (DT and SP) for the T3 group might indicate that S1-1 generally provides better conditions for cognitive performance. However, it is important to note that the effect is less pronounced in the SP task compared to the DT task.

H.5 Kruskal-Wallis test results

Below are the results of the Kruskal-Wallis test, which was used to compare the 'Scores' across three different test conditions in three separate classrooms. However, while the Kruskal-Wallis test can indicate whether there is a difference among the groups, it doesn't specify which groups differ.

If the Kruskal-Wallis test indicates that at least one group is different, post-hoc tests are performed to identify exactly which groups differ. Dunn's test has been used to make these pairwise comparisons between groups while controlling for Type I errors.

A Bonferroni adjustment is applied to control further the familywise error rate, which is the probability of making one or more false discoveries when performing multiple hypotheses tests. This adjustment helps to maintain the overall significance level by dividing the significance threshold (α) by the number of comparisons being made (MacFarland and Yates, 2016).

In summary:

- Kruskal-Wallis Test: Detects if there is an overall difference among groups.
- Dunn's Test: Identifies which specific groups differ.
- Bonferroni Adjustment: Controls for the increased risk of Type I errors due to multiple comparisons.

This combination ensures that the process is both comprehensive and statistically rigorous.

H.5.1 Double Trouble

Kruskal-Wallis test for S1-1 and S1-3 is not significant. The findings of Dunn's test for S1-2 reveal the following insights:

T1 vs T2:

- Z-value: -3.166
- p -value: 0.0007
- p .adjusted: 0.002
- Interpretation: The p .adjusted value (0.002) is less than the significance level ($\alpha = 0.05$). This indicates a significant difference between T1 (Normal) and T2 (Marginally elevated warmth).

T1 vs T3:

- Z-value: -1.414
- p -value: 0.078
- p .adjusted: 0.235
- Interpretation: The p .adjusted value (0.235) is greater than the significance level ($\alpha = 0.05$). This suggests no significant difference between T1 (Normal) and T3 (Elevated CO₂ and temperature).

T2 vs T3:

- Z-value: 1.547
- p -value: 0.060
- p .adjusted: 0.182
- Interpretation: The p .adjusted value (0.182) is greater than the significance level ($\alpha = 0.05$). This suggests no significant difference between T2 (Marginally elevated warmth) and T3 (Elevated CO₂ and temperature).

H.5.2 Spatial Planning

The Kruskal-Wallis test for S1-1 is not significant. The findings of Dunn's test for S1-2 reveal the following insights:

T1 vs. T2

- Z-score: -3.216
- p -value: 0.0006 (significant at $p < 0.05$)
- Adjusted p -value: 0.001 (significant at $p < 0.025$)
- Outcome: T1 significantly differs from T2.

T1 vs. T3

- Z-score: -0.713
- p -value: 0.237 (not significant)
- Adjusted p -value: 0.713 (not significant at $p > 0.025$)
- Outcome: No significant difference between T1 and T3.

T2 vs. T3

- Z-score: 2.446
- p -value: 0.007 (marginally significant)
- Adjusted p -value: 0.021 (significant at $p < 0.025$)
- Outcome: T2 significantly differs from T3.

Interpretation of results

- **Normal (T1) vs. Marginally elevated warmth (T2):** Significant difference indicates that the environment or performance under normal conditions is notably distinct from conditions where the warmth is moderately increased.
- **Normal (T1) vs. Elevated CO₂ and temperature (T3):** No significant difference suggests that the elevated CO₂ and temperature, along with face mask usage, do not sufficiently impact performance or conditions compared to the normal environment.
- **Marginally elevated warmth (T2) vs. Elevated CO₂ and temperature (T3):** Significant difference implies that the environment under marginally elevated warmth conditions is notably distinct from the environment with both increased CO₂ levels and temperature elevation, compounded by mask usage.

The findings of Dunn's test for S1-3 reveal the following insights:

T1 vs. T2

- Z-score: -2.931
- p -value: 0.001 (significant at $p < 0.05$)
- Adjusted p -value: 0.005 (significant at $p < 0.025$)
- Conclusion: Significant difference between T1 and T2.

T1 vs. T3

- Z-score: -2.185
- p -value: 0.014 (significant at $p < 0.05$)
- Adjusted p -value: 0.043 (not significant at $p > 0.025$)
- Conclusion: No significant difference between T1 and T3 after adjustment.

T2 vs. T3

- Z-score: 0.200
- p -value: 0.420 (not significant)
- Adjusted p -value: 1.000 (not significant)
- Conclusion: No significant difference between T2 and T3.

Interpretation of results

- **T1 vs. T2 (Normal vs. Marginally elevated warmth):** The significant difference indicates that the environment or performance changes notably under the marginally elevated warmth condition compared to the normal condition.
- **T1 vs. T3 (Normal vs. Elevated CO₂ and temperature):** Initially found significant, the adjustment reveals no significant difference in conditions between T1 and T3, suggesting the elevated CO₂ and temperature, along with mask usage, might not drastically affect the environment or performance compared to normal conditions.

- **T2 vs. T3 (Marginally elevated warmth vs. elevated CO₂ and temperature):** No significant difference indicates that the environment or performance under marginally elevated warmth conditions is quite similar to that under elevated CO₂ and temperature conditions.
- **Effect of comfort on performance:** The results suggest that a more comfortable and naturally ventilated environment (T1) leads to better student performance. As conditions become less comfortable (T2 and T3), performance tends to decline.
- **Impact of warmth and CO₂:** The conditions in T2 and T3 introduced elements of warmth and higher CO₂ levels. These factors seem to negatively affect performance, possibly due to discomfort or decreased cognitive function.
- **Comparative insights:** While T2 and T3 both induce discomfort, T2 (slightly elevated warmth) appears to be slightly more detrimental than T3 (both elevated heat and CO₂ with face masks), though the difference is minimal.

H.5.3 Spatial Span

Kruskal-Wallis test for S1-1, S1-2 and S1-3 is not significant. The findings of Dunn's test for S1-2 reveal the following insights:

T1 vs. T2

- Z-score: -2.663
- p -value: 0.003 (significant at $p < 0.05$)
- Adjusted p -value: 0.011 (significant at $p < 0.025$)
- Conclusion: Significant difference between T1 and T2.

T1 vs. T3

- Z-score: -0.928
- p -value: 0.176 (not significant)
- Adjusted p -value: 0.530 (not significant)
- Conclusion: No significant difference between T1 and T3.

T2 vs. T3

- Z-score: 1.566
- p -value: 0.058 (not significant)
- Adjusted p -value: 0.176 (not significant)
- Conclusion: No significant difference between T2 and T3.

Interpretation of results

- **T1 (Normal) vs T2 (Marginally elevated warmth):** There is a significant difference, indicating that the changes in the warmth condition (T2) without student awareness notably affect the environment or performance compared to the normal condition (T1).
- **T1 (Normal) vs. T3 (Elevated CO₂ and temperature):** No significant difference, suggesting that even with elevated CO₂ and temperature conditions, compounded by mask usage, the change does not significantly impact the environment or performance in comparison to the normal condition (T1).
- **T2 (Marginally elevated warmth) vs. T3 (Elevated CO₂ and temperature):** No significant difference between these conditions, indicating that both marginal warmth increase and elevated CO₂ and temperature (with masks) affect the environment similarly.

H.6 Impact of time on cognitive tests

Section H.5 corresponds to the analysis in Chapter 7, section 7.3

H.6.1 Double Trouble

Figure H.1 details the results of the Variance (ANOVA) DT results and Normality test for 'Room', 'Test Condition', and 'Time of Day Effects'

FIGURE H.1: Analysis of Variance (ANOVA) DT Results and Normality Test for Room, Test Condition, and Time of Day Effects

```
Print the summary of the ANOVA
summary(anova_result)

      Df Sum Sq Mean Sq F value    Pr(>F)
Room      2    4019     2009   11.291 1.81e-05 ***
EnvironType 2    2203     1102    6.191  0.0023 **
TimeOfDay   1    6758     6758   37.973 2.12e-09 ***
Room:EnvironType 4     669      167    0.940  0.4407
Room:TimeOfDay 2     796      398    2.236  0.1085
EnvironType:TimeOfDay 1     430      430    2.417  0.1210
Room:EnvironType:TimeOfDay 1     311      311    1.747  0.1872
Residuals 326   58017      178

---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Check assumptions
1. Normality

Shapiro-Wilk normality test

data:  residuals(anova_result)
W = 0.98533, p-value = 0.001568

2. Homogeneity of variances
leveneTest(Score ~ interaction( testName , TimeOfDay, EnvironType), data = my_data)
Levene's Test for Homogeneity of Variance (center = median)
      Df    F value    Pr(>F)
group  5    0.6143    0.689
      334
```

Based on the ANOVA results in **Figure H.1**, the following important insights regarding the cognitive performances of the students under different environmental conditions, times of the day, and across different rooms can be drawn:

- **Room:** The effect of the room on cognition is highly significant (p -value = $1.81e-05$), suggesting that the cognitive performance varied significantly across the different rooms.
- **EnvironType (akaTestCondition):** The test condition (T1, T2, T3) has a significant effect on cognitive performance (p -value = 0.0023), indicating that the room conditions do impact student cognition.
- **TimeOfDay:** The time of day was highly significant (p -value = $2.12e-09$). This shows that cognitive performance significantly differs depending on whether the test is conducted in the morning or the afternoon.
- **Room:EnvironType (akaTestCondition):** The interaction between room and test condition is not significant (p -value = 0.4407), meaning the effect of the test condition does not significantly vary across different rooms.
- **Room:TimeOfDay:** The interaction between room and time of day is marginally significant (p -value = 0.1085), indicating a slight variation in the effect of the

time of day across different rooms but not strongly enough to conclude a significant interaction.

- **EnvironType (akaTestCondition):TimeOfDay:** The interaction between test condition and time of day also does not show significant effects (p -value = 0.1210), indicating that the impact of the test condition on cognitive performance does not change significantly depending on the time of day.
- **Room:EnvironType (akaTestCondition):TimeOfDay:** Similarly, the three-way interaction between room, test condition, and time of day is not significant (p -value = 0.1872), suggesting that combining these three factors does not significantly alter cognitive performance.
- The Shapiro-Wilk test for normality has a very low p -value ($p = 0.001568$), indicating that the residuals are not normally distributed. This could somewhat affect the validity of the ANOVA results.
- Levene's Test shows a p -value of 0.689, which is not significant, suggesting that the variance across groups is homogeneous and this assumption of the ANOVA has been met.

Pairwise Comparisons for Time of Day within Each Test Condition:

Figure H.2 outlines the pairwise comparisons for 'Time of Day' within each test condition.

FIGURE H.2: Statistical Comparison of Room Contrasts by Time of Day and Test Condition for DT

TimeOfDay = AM, EnvironType = T1:						
contrast	estimate	SE	df	t.ratio	p.value	
Room5 - Room6	4.59	3.47	326	1.320	0.3848	
Room5 - Room7	7.29	4.00	326	1.820	0.1645	
Room6 - Room7	2.70	3.98	326	0.679	0.7760	
TimeOfDay = PM, EnvironType = T1:						
contrast	estimate	SE	df	t.ratio	p.value	
Room5 - Room6	nonEst	NA	NA	NA	NA	
Room5 - Room7	21.41	4.35	326	4.923	<.0001	
Room6 - Room7	nonEst	NA	NA	NA	NA	
TimeOfDay = AM, EnvironType = T2:						
contrast	estimate	SE	df	t.ratio	p.value	
Room5 - Room6	1.58	3.04	326	0.519	0.8621	
Room5 - Room7	4.14	4.07	326	1.016	0.5670	
Room6 - Room7	2.56	3.69	326	0.695	0.7665	
TimeOfDay = PM, EnvironType = T2:						
contrast	estimate	SE	df	t.ratio	p.value	
Room5 - Room6	3.62	5.17	326	0.700	0.7637	
Room5 - Room7	6.44	5.34	326	1.206	0.4503	
Room6 - Room7	2.83	5.06	326	0.559	0.8419	
TimeOfDay = AM, EnvironType = T3:						
contrast	estimate	SE	df	t.ratio	p.value	
Room5 - Room6	nonEst	NA	NA	NA	NA	
Room5 - Room7	nonEst	NA	NA	NA	NA	
Room6 - Room7	nonEst	NA	NA	NA	NA	
TimeOfDay = PM, EnvironType = T3:						
contrast	estimate	SE	df	t.ratio	p.value	
Room5 - Room6	nonEst	NA	NA	NA	NA	
Room5 - Room7	7.31	4.27	326	1.712	0.0879	
Room6 - Room7	nonEst	NA	NA	NA	NA	

Based on the provided pairwise comparisons and context (**Figure H.2**), the following can be ascertained:

1. **Significant difference in PM for T1:** There's a statistically significant difference between S1-1 and S1-3 in the afternoon (PM) for the normal classroom environment (T1). The p -value is <.0001, indicating strong evidence of difference.
2. **Limited data for some comparisons:** Several comparisons show "nonEst" (non-estimable) results, particularly for S1-2 in PM sessions and all rooms in T3 (elevated CO₂ and temperature) AM sessions. This could be due to missing data or insufficient sample size for these conditions.

3. **No significant differences in most comparisons:** Most of the comparisons show p -values > 0.05 , indicating no statistically significant differences between rooms for those conditions.
4. **Variation in estimate magnitudes:** The estimates vary in magnitude across different conditions, suggesting that the impact of environmental conditions on cognitive performance might differ depending on the time of day and specific environmental setup.
5. **Highest estimate in PM for T1:** The largest estimated difference (21.41) is observed between S1-1 and S1-3 in the afternoon for the normal environment (T1).
6. **Consistency in AM sessions:** Morning (AM) sessions generally show more consistent results across rooms and test conditions, with fewer "nonEst" occurrences.
7. **Potential impact of environmental conditions:** The differences in results across T1, T2, and T3 suggest that the different environmental conditions (normal, marginally elevated warmth, and elevated CO₂/temperature) might influence cognitive performance differently.
8. **Time of day effect:** There are differences between AM and PM results, indicating that time of day might affect cognitive performance or how students respond to different environmental conditions.

These observations provide insights into how different classroom environments and times of day might affect cognitive performance among primary school students. However, non-estimable results suggest that more data or further investigation might be needed to understand all conditions comprehensively.

Table H.10 details the changes in the mean scores by Room and Test condition for DT.

TABLE H.10: Mean Scores by Room and Test Condition for DT

```
> print(mean_scores)
# A tibble: 9 × 3
# Groups:   Room [3]
  Room EnvironType mean_score
<fct> <fct>          <dbl>
1 5      T1          23.7
2 5      T2          23.8
3 5      T3          30.6
4 6      T1          12.0
5 6      T2           21
6 6      T3          16.8
7 7      T1          15.0
8 7      T2          20.1
9 7      T3          23.2
```

Based on the data from (Table 7.3) and score changes (Table H.10), the following can be identified:

Temperature changes and Score changes: S1-1:

- T1 to T2:
- Temperature change: $23.89 - 23.64 = 0.25$ °C increase
- Score change: $23.8 - 23.7 = 0.1$ point increase
- Ratio: $0.1 / 0.25 = 0.4$ points per °C
- T1 to T3:
- Temperature change: $24.60 - 23.64 = 0.96$ °C increase
- Score change: $30.6 - 23.7 = 6.9$ point increase
- Ratio: $6.9 / 0.96 = 7.19$ points per °C

S1-2:

- T1 to T2:
- Temperature change: $25.03 - 24.10 = 0.93$ °C increase

- Score change: $21.0 - 12.0 = 9.0$ point increase
- Ratio: $9.0 / 0.93 = 9.68$ points per $^{\circ}\text{C}$
- T1 to T3:
- Temperature change: $24.68 - 24.10 = 0.58$ $^{\circ}\text{C}$ increase
- Score change: $16.8 - 12.0 = 4.8$ point increase
- Ratio: $4.8 / 0.58 = 8.28$ points per $^{\circ}\text{C}$

S1-3:

- T1 to T2:
- Temperature change: $21.42 - 21.81 = -0.39$ $^{\circ}\text{C}$ decrease
- Score change: $20.1 - 15.0 = 5.1$ point increase
- Ratio: $5.1 / -0.39 = -13.08$ points per $^{\circ}\text{C}$ (inverse relationship)
- T1 to T3:
- Temperature change: $22.98 - 21.81 = 1.17$ $^{\circ}\text{C}$ increase
- Score change: $23.2 - 15.0 = 8.2$ point increase
- Ratio: $8.2 / 1.17 = 7.01$ points per $^{\circ}\text{C}$

CO₂ changes and Score changes: S1-1:

- T1 to T2:
- CO₂ change: $864.00 - 567.60 = 296.40$ ppm increase
- Score change: $23.8 - 23.7 = 0.1$ point increase
- Ratio: $0.1 / 296.40 = 0.0003$ points per ppm CO₂
- T1 to T3:
- CO₂ change: $1148.58 - 567.60 = 580.98$ ppm increase
- Score change: $30.6 - 23.7 = 6.9$ point increase

- Ratio: $6.9 / 580.98 = 0.0119$ points per ppm CO₂

S1-2:

- T1 to T2:
 - CO₂ change: $765.88 - 550.88 = 215.00$ ppm increase
 - Score change: $21.0 - 12.0 = 9.0$ point increase
 - Ratio: $9.0 / 215.00 = 0.0419$ points per ppm CO₂
- T1 to T3:
 - CO₂ change: $1134.50 - 550.88 = 583.62$ ppm increase
 - Score change: $16.8 - 12.0 = 4.8$ point increase
 - Ratio: $4.8 / 583.62 = 0.0082$ points per ppm CO₂

S1-3:

- T1 to T2:
 - CO₂ change: $685.88 - 529.50 = 156.38$ ppm increase
 - Score change: $20.1 - 15.0 = 5.1$ point increase
 - Ratio: $5.1 / 156.38 = 0.0326$ points per ppm CO₂
- T1 to T3:
 - CO₂ change: $1476.00 - 529.50 = 946.50$ ppm increase
 - Score change: $23.2 - 15.0 = 8.2$ point increase
 - Ratio: $8.2 / 946.50 = 0.0087$ points per ppm CO₂

Interpretation of results

Temperature changes:

1. In most cases, an increase in temperature is associated with increased scores.
2. S1-3 shows an inverse relationship between temperature and score for T1 to T2, similar to the previous test.
3. The largest score increases per °C are observed in S1-2 for both T1 to T2 (9.68 points/ °C) and T1 to T3 (8.28 points/ °C).
4. S1-1 shows a much larger increase in score per °C for T1 to T3 (7.19 points/ °C) compared to T1 to T2 (0.4 points/ °C).

CO₂ changes:

1. All rooms show an increase in scores with increasing CO₂ levels.
2. For T1 to T2 transitions:
 - S1-2 shows the highest score increase per ppm CO₂ (0.0419 points/ppm)
 - S1-1 shows the lowest score increase per ppm CO₂ (0.0003 points/ppm)
3. For T1 to T3 transitions:
 - The score increase per ppm CO₂ is more consistent across rooms (0.0082 to 0.0119 points/ppm)
 - These ratios are generally lower than those for T1 to T2 transitions, except for S1-1

Interpretation of results

- The relationship between environmental changes and score changes varies significantly between rooms and conditions.
- In general, both temperature and CO₂ increases are associated with improved scores on the DT test.
- The impact of environmental changes seems to be more pronounced in S1-2 and S1-3 compared to S1-1.

- The T2 condition (T2) often shows larger improvements in scores per unit change in temperature or CO₂ compared to the T3 condition (T3).
- The results suggest a non-linear relationship between environmental factors and cognitive performance, as the effects are inconsistent across all ranges of temperature and CO₂ changes.
- S1-3's inverse temperature-score relationship in T1 to T2 suggests that other factors may influence the results, and the relationship between temperature and cognitive performance is complex.

These findings highlight the complex interplay between environmental factors and cognitive performance, suggesting that moderate temperature and CO₂ levels may affect cognitive function. Still, these effects may vary depending on the specific conditions and individual rooms.

H.6.2 Spatial Planning

Figure H.3 details the results of the Variance (ANOVA) SP results and Normality test for 'Room', 'Test Condition', and 'Time of Day Effects'

FIGURE H.3: Analysis of Variance (ANOVA) SP Results and Normality Test for Room, Test Condition, and Time of Day Effects

```
# Print the summary of the ANOVA
summary(anova_result)

      Df Sum Sq Mean Sq F value    Pr(>F)
Room      2      777    388.6    5.348 0.00517 **
EnvironType 2     1546    772.9   10.636 3.32e-05 ***
TimeOfDay    1     1612   1611.8   22.179 3.64e-06 ***
Room:EnvironType 4        69     17.2    0.236 0.91776
Room:TimeOfDay 2       453    226.5    3.117 0.04559 *
EnvironType:TimeOfDay 1        16     16.4    0.226 0.63468
Room:EnvironType:TimeOfDay 1        1     1.1    0.015 0.90322
Residuals 335    24345     72.7

---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

# Check assumptions
# 1. Normality

Shapiro-Wilk normality test

data:  residuals(anova_result)
W = 0.98886, p-value = 0.009107

# 2. Homogeneity of variances
leveneTest(Score ~ interaction( testName , TimeOfDay, EnvironType), data = my_data)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  5  0.9098 0.4747
      343
```

From the ANOVA results (**Figure H.3**), we can see that Room, EnvironType (aka Test condition), and TimeOfDay all have a significant impact on student cognitive performance in primary school classrooms. The different combinations of these factors (Room:EnvironType (aka Test condition), Room:TimeOfDay, EnvironType (aka Test condition):TimeOfDay, Room:EnvironType (aka Test condition):TimeOfDay) did not show significant effects.

Specifically, the EnvironType (aka Test condition) factor had the largest impact on student cognitive performance, with the Normal classroom environment performing significantly better than the T3 and T2 environments. Time of day also had a significant impact, with cognitive performance being higher in the afternoon compared to the morning.

Based on this information, we can ascertain that classroom environment conditions (T1, T3, T2) and time of day (morning vs. afternoon) significantly impact student cognitive performance in primary school classrooms. This suggests optimizing classroom conditions and scheduling cognitive tests in the afternoon may improve cognitive performance in Year 5 and Year 6 students.

Figure H.4 outlines each test condition's pairwise comparisons for 'Time of Day'.

FIGURE H.4: Statistical Comparison of Room Contrasts by Time of Day and Test Condition

```
> #Compare TimeOfDay within each combination of EnvironType and TestName:
> emm_re <- emmeans(anova_result, ~ Room | TimeOfDay | EnvironType)
> pairs(emm_re)
```

TimeOfDay = AM, EnvironType = T1:

contrast	estimate	SE	df	t.ratio	p.value
Room5 - Room6	1.906	2.19	335	0.870	0.6595
Room5 - Room7	1.442	2.53	335	0.569	0.8367
Room6 - Room7	-0.464	2.46	335	-0.189	0.9805

TimeOfDay = PM, EnvironType = T1:

contrast	estimate	SE	df	t.ratio	p.value
Room5 - Room6	nonEst	NA	NA	NA	NA
Room5 - Room7	7.681	2.77	335	2.774	0.0058
Room6 - Room7	nonEst	NA	NA	NA	NA

TimeOfDay = AM, EnvironType = T2:

contrast	estimate	SE	df	t.ratio	p.value
Room5 - Room6	1.680	1.96	335	0.859	0.6666
Room5 - Room7	1.980	2.60	335	0.760	0.7276
Room6 - Room7	0.299	2.37	335	0.127	0.9912

TimeOfDay = PM, EnvironType = T2:

contrast	estimate	SE	df	t.ratio	p.value
Room5 - Room6	-0.033	3.28	335	-0.010	0.9999
Room5 - Room7	7.538	3.23	335	2.334	0.0526
Room6 - Room7	7.571	3.17	335	2.390	0.0457

TimeOfDay = AM, EnvironType = T3:

contrast	estimate	SE	df	t.ratio	p.value
Room5 - Room6	nonEst	NA	NA	NA	NA
Room5 - Room7	nonEst	NA	NA	NA	NA
Room6 - Room7	nonEst	NA	NA	NA	NA

TimeOfDay = PM, EnvironType = T3:

contrast	estimate	SE	df	t.ratio	p.value
Room5 - Room6	nonEst	NA	NA	NA	NA
Room5 - Room7	2.231	2.64	335	0.847	0.3978
Room6 - Room7	nonEst	NA	NA	NA	NA

Analysis based on p -values from pairwise comparison from **Figure H.4** the following can be ascertained:

Test 1 condition:

- There are no significant differences in cognitive performance between S1-1, S1-2, and S1-3 in the morning (AM).
- In the afternoon (PM), there is a significant difference between S1-1 and S1-3, with S1-1 performing significantly better.
- There are no significant differences between S1-2 and S1-3 in the morning or afternoon.

Test 2 condition:

- There are no significant differences in cognitive performance between S1-1, S1-2, and S1-3 in the morning.
- In the afternoon, there is a significant difference between S1-1 and S1-3, with S1-1 performing significantly better.
- There is also a significant difference between S1-2 and S1-3 in the afternoon, with S1-2 performing significantly better.

Test 3 condition - There are no estimable contrasts for any combinations of S1-1, S1-2, and S1-3 in both the morning and afternoon.

Overall, the results suggest that the T1 and T2 impact cognitive performance in the afternoon, with S1-1 performing better than S1-3. However, T3 does not show significant differences in cognitive performance between the rooms.

Table H.10 details the changes in the mean scores by Room and Test condition for SP.

TABLE H.11: Mean Scores by Room and Test Condition for SP

```
print(mean_scores)
# A tibble: 9 × 3
# Groups:   Room [3]
  Room EnvironType mean_score
<fct> <fct>          <dbl>
1 5      T1          21.8
2 5      T2          25.9
3 5      T3          25.1
4 6      T1          17.3
5 6      T2          23.9
6 6      T3          19.3
7 7      T1          19.1
8 7      T2          22.4
9 7      T3          22.9
```

Using data from **Table 7.3** and score changes **Table H.11**, the following can be inferred:

Temperature and score:

S1-1:

- T1 to T2:
- Temperature change: $23.89 - 23.64 = 0.25$ °C increase
- Score change: $25.9 - 21.8 = 4.1$ point increase
- Ratio: $4.1 / 0.25 = 16.4$ points per °C
- T1 to T3:
- Temperature change: $24.60 - 23.64 = 0.96$ °C increase
- Score change: $25.1 - 21.8 = 3.3$ point increase
- Ratio: $3.3 / 0.96 = 3.44$ points per °C

S1-2:

- T1 to T2:
- Temperature change: $25.03 - 24.10 = 0.93$ °C increase

- Score change: $23.9 - 17.3 = 6.6$ point increase
- Ratio: $6.6 / 0.93 = 7.10$ points per $^{\circ}\text{C}$
- T1 to T3:
- Temperature change: $24.68 - 24.10 = 0.58$ $^{\circ}\text{C}$ increase
- Score change: $19.3 - 17.3 = 2.0$ point increase
- Ratio: $2.0 / 0.58 = 3.45$ points per $^{\circ}\text{C}$

S1-3:

- T1 to T2:
- Temperature change: $21.42 - 21.81 = -0.39$ $^{\circ}\text{C}$ decrease
- Score change: $22.4 - 19.1 = 3.3$ point increase
- Ratio: $3.3 / -0.39 = -8.46$ points per $^{\circ}\text{C}$ (inverse relationship)
- T1 to T3:
- Temperature change: $22.98 - 21.81 = 1.17$ $^{\circ}\text{C}$ increase
- Score change: $22.9 - 19.1 = 3.8$ point increase
- Ratio: $3.8 / 1.17 = 3.25$ points per $^{\circ}\text{C}$

Interpretation of results:

1. In most cases, an increase in temperature is associated with increased scores.
2. The relationship between temperature and score change varies significantly between rooms and conditions.
3. S1-3 shows an inverse relationship between temperature and score for T1 to T2, which is unique compared to other rooms and conditions.
4. The largest score increase per degree Celsius is observed in S1-1 for T1 to T2 (16.4 points/ $^{\circ}\text{C}$).
5. For T1 to T3 transitions, the score increase per degree Celsius is relatively consistent across rooms (3.25 to 3.45 points/ $^{\circ}\text{C}$).

6. The relationship between temperature and score is not linear and is likely influenced by other factors, as evidenced by the varying ratios across rooms and conditions.

CO₂ level changes and score

S1-1:

- T1 to T2:
- CO₂ change: $864.00 - 567.60 = 296.40$ ppm increase
- Score change: $25.9 - 21.8 = 4.1$ point increase
- Ratio: $4.1 / 296.40 = 0.0138$ points per ppm CO₂
- T1 to T3:
- CO₂ change: $1148.58 - 567.60 = 580.98$ ppm increase
- Score change: $25.1 - 21.8 = 3.3$ point increase
- Ratio: $3.3 / 580.98 = 0.0057$ points per ppm CO₂

S1-2:

- T1 to T2:
- CO₂ change: $765.88 - 550.88 = 215.00$ ppm increase
- Score change: $23.9 - 17.3 = 6.6$ point increase
- Ratio: $6.6 / 215.00 = 0.0307$ points per ppm CO₂
- T1 to T3:
- CO₂ change: $1134.50 - 550.88 = 583.62$ ppm increase
- Score change: $19.3 - 17.3 = 2.0$ point increase
- Ratio: $2.0 / 583.62 = 0.0034$ points per ppm CO₂

S1-3:

- T1 to T2:

- CO₂ change: $685.88 - 529.50 = 156.38$ ppm increase
- Score change: $22.4 - 19.1 = 3.3$ point increase
- Ratio: $3.3 / 156.38 = 0.0211$ points per ppm CO₂
- T1 to T3:
- CO₂ change: $1476.00 - 529.50 = 946.50$ ppm increase
- Score change: $22.9 - 19.1 = 3.8$ point increase
- Ratio: $3.8 / 946.50 = 0.0040$ points per ppm CO₂

Interpretation of results:

1. In all cases, an increase in CO₂ levels is associated with an increase in scores.
2. The relationship between CO₂ change and score change varies between rooms and conditions.
3. For T1 to T2 transitions:
 - S1-2 shows the highest score increase per ppm CO₂ (0.0307 points/ppm)
 - S1-1 shows the lowest score increase per ppm CO₂ (0.0138 points/ppm)
4. For T1 to T3 transitions:
 - The score increase per ppm CO₂ is more consistent across rooms (0.0034 to 0.0057 points/ppm)
 - These ratios are lower than those for T1 to T2 transitions, suggesting diminishing returns as CO₂ levels increase further
5. The larger increases in CO₂ levels for T3 conditions do not correspond to proportionally larger increases in scores, indicating a non-linear relationship.
6. The impact of CO₂ on scores appears to be more pronounced in the T2 condition (T2) compared to the T3 condition (T3), possibly due to the interaction with other environmental factors like temperature and humidity.

Observations by Environmental test condition and Time of day

- Test 1 - AM
 - S1-1 has the lowest mean.
 - S1-2 and S1-3 have slightly higher means, indicating possibly better conditions or responses to the teacher-managed environment.
- Test 2 - AM
 - There is an increase in emmeans compared to T1, especially in S1-1.
 - Rooms S1-2 and S1-3 show moderate differences, possibly reflecting the impact of the covert heater use.
- Test 3 - AM
 - S1-3 shows higher emmeans than T1 and T2, suggesting the combined effect of elevated CO₂ and temperature might affect the rooms differently.
- Test 1 - PM
 - Notable increase in emmeans for Rooms S1-1 and S1-3 compared to AM, indicating afternoon conditions might be more favourable or have a different impact.
 - S1-2 maintains a relatively consistent mean between AM and PM, with a slight increase in the PM session.
- Test 2 - PM
 - Higher emmeans are observed in S1-3 compared to S1-1 and S1-2, indicating possibly more awareness and discomfort due to the covert heating.
- Test 3 - PM
 - Significant increase in emmeans for S1-3, and moderate increases for S1-1 and S1-2.
 - Face masks and elevated CO₂ and temperature might influence these metrics, showing increased values.

- **General observations:**
 - Rooms exhibit different responses to the various environmental conditions, suggesting that ventilation, heating, and CO₂ conditions might affect each room's environment and the occupants' reactions differently.
- **Comparison across conditions:**
 - T1 (Natural Ventilation) generally shows lower estimated marginal means (emmeans), suggesting that students might feel more comfortable or perform better in naturally ventilated environments with fresh air flow due to open windows and doors.
 - T2 (Marginally Elevated Warmth) displays varied responses across rooms, with some participants showing increased awareness or discomfort due to the subtle heating. This marginal increase in temperature may impact performance or perception without clear communication, leading to inconsistency.
 - T3 (Elevated CO₂ and Temperature) shows the highest emmeans, particularly in the PM sessions. The combination of elevated CO₂, temperature, and face masks likely contributes to discomfort, possibly due to increased CO₂ and the cumulative effect of the environmental stressors.
- There is a noticeable difference between AM and PM sessions across all environmental conditions, suggesting potential diurnal variations in comfort or performance metrics. Rooms generally show higher mean values in the PM, possibly due to an accumulation of heat or CO₂ over the day or students' acclimatization.
- **Room-Specific and Condition-Specific Insights:**
 - S1-1: Exhibits significant variation between the different test conditions, especially noticeable in T1 PM, where it has the highest mean. This might indicate that during naturally ventilated conditions, S1-1 might have structural or functional traits (like draft patterns or window placements) that enhance or degrade comfort more noticeably.
 - S1-2: Displays more consistent means across different conditions than the other rooms. However, under T3 in the PM, there's a slight increase,

which might indicate lesser sensitivity to lower CO₂ fluctuations but clear response to elevated temperatures and/or prolonged face mask usage.

- S1-3: Shows distinct spikes under T3, especially in the PM session, hinting that S1-3 might experience greater CO₂ accumulation or heat retention. The participants here also might be more sensitive to these changes, or other confounding factors could influence the readings.

It is important to note that these relationships are complex and likely influenced by multiple factors beyond just CO₂ levels. The data suggests that moderate increases in CO₂ (as seen in T2) may have a more positive impact on scores than larger increases (as seen in T3).

Appendix I

Further research example

I.1 Introduction

In this chapter, the PI will delve into a segment of research that was ultimately excluded due to ethical considerations and the unprecedented impacts of the COVID-19 pandemic.

Specifically, this section focusses on the proposed use of a 14-channel EEG gaming device to measure beta brainwaves. Although the original intent was to harness this technology to gain deeper insights into cognitive processes whilst the students were undertaking the online cognitive tests, the unforeseen global health crisis and stringent ethical guidelines necessitated a re-evaluation and subsequent exclusion of this component from the study.

However, the PI believed that this component would provide unparalleled visual output, so it was decided to investigate adult participants. However, this section of the research study will only begin in July 2024, so the outcomes will not be part of this thesis.

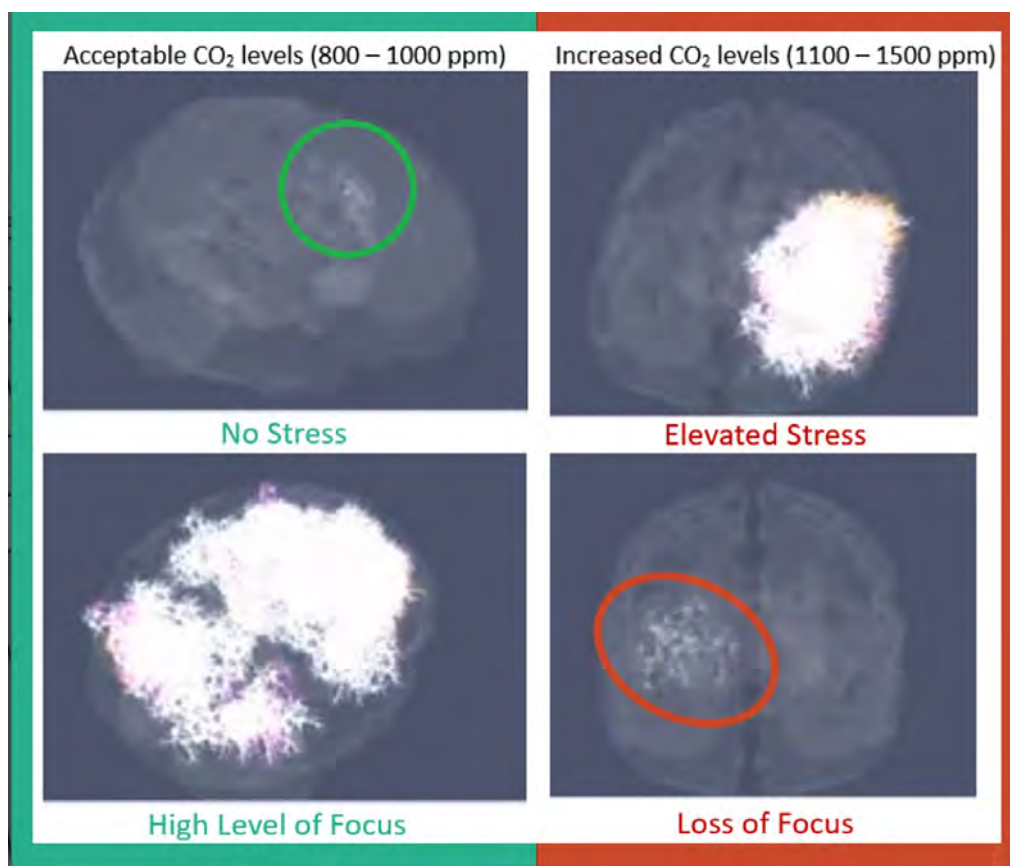
In 2018, the PI conducted a pilot study with the Bachelor of Construction cohort. During this study, an adult participant performed a simple cognitive typing test in an environmental chamber, where the temperature was maintained at a steady 22°C. The initial test was conducted at a low CO₂ level (800 - 1000 ppm), called the green band.

As shown in **Figure I.1**, the participant's brain exhibited minimal stress in the green band in the upper left, indicated by low cortisol levels. The participant remained

highly focused on the task (bottom left green band). However, as CO₂ levels increased to 1100 - 1500 ppm (red band), considered acceptable in NZ schools before COVID-19, noticeable changes in brain activity were observed.

Figure I.1, top right red band, displays an increase in stress levels, partly due to a spike in cortisol hormone, which could be up to nine times higher (Clay, 2018). In the bottom right red band, the participant demonstrated only marginal levels of focus, indicating that this higher CO₂ environment would not be suitable for introducing learning concepts that require substantial recall and problem solving abilities.

FIGURE I.1: *Relationship between CO₂ Levels, Stress and Focus*



Unfortunately, only one of the two results of the pilot study can be shown. The second participant did not maintain a steady state during EEG testing, leading to interruptions in imaging data. Consequently, the results of this second participant are not available for analysis.

These tests were carried out before the COVID-19 pandemic. Given the powerful insights that brain mapping imaging provided, the PI decided that it would effectively demonstrate the importance of proper ventilation to teachers and other interested parties, such as the MoE and parents. The study highlights the clear impact of CO₂ levels on brain function and the need to maintain well-aired learning environments.

I.2 Using an EEG in built environment research

EEG is commonly used to conduct research on epileptic seizures, sleep disorders (Chancellor, 2009; Tatum IV, 2014) and attention deficit / hyperactivity disorders (ADHD) (Woo et al., 2022; Turunen et al., 2012). It has also been used in the detection of lies (Cook and Mitschow, 2019), pharmacological analysis, and evaluation of cognitive dysfunction caused by neurological disorders (Lenzi and Bonsanto, 2018; Sanei and Chambers, 2013).

However, various studies exploring attention and concentration using EEG measurements have been published in different subject areas, including education, physical education, and ergonomics (Derbali et al., 2011). EEG studies are applied to spatial cognition, architecture, urban design, planning, environmental psychology, and spatial analysis (Aspinall et al., 2015; Mavros et al., 2016). Jebelli, Khalili and Lee (2018) and Habibnezhad et al. (2020) are researching construction stress on site with an EEG to improve workers' health. This review suggests that EEG could be suitable for research in the built environment.

The Emotive Epoc+ device was originally developed for gaming. Epoc+ can detect a user's thoughts, feelings, and expressions by capturing the brainwaves produced by the wearer (Harrison, 2013). Over the years, Epoc+ became more popular in other areas of research (Table I.1).

TABLE I.1: Summary of Emotiv Epoc Studies

Reference	Study	Participant info	Result
Aspinall, Mavros, Coyne & Roe (2015)	The urban brain: Analysing outdoor physical activity with mobile EEG	12 participants (8 m; 4 f) (mean age 30.08 years) Edinburgh University	Transitions between zones identifiable (urban shopping street to green space) reductions in arousal, frustration, and engagement (i.e., directed attention), and an increase in meditation.
Goldberg, Brawner & Holden (2012)	Efficacy of Measuring Engagement during Computer-Based Training with Low-Cost Electroencephalogram (EEG) Sensor Outputs	79 cadets – USA West Point Military Academy (59 m; 20 f) (18 – 25 years)	The research supports Emotiv's ability to track engagement and excitement trends as they relate to learning events.
Matlovic, Gaspar, Moro, Simko & Bielikova (2016)	Emotions Detection Using Facial Expressions Recognition and EEG	Nine participants (8 m; 1 f) Slovak University	The results achieved on the acquired dataset (58% accuracy) suggest that there is still room for improvement.
Rodriguez, Rey, & Alcañiz (2013)	Validation of a Low-Cost EEG Device for Mood Induction Studies	16 university students (8 m; 8 f) (23 – 30 years) Spain	This results support the possibility of using low-cost EEG devices, as an emotional measuring tool in future studies.
Seco, Gerhardt, Biazotti, Molan, Schönwaldc & Rybarczyk-Filhoa (2019)	EEG alpha rhythm detection on a portable device	10 undergraduate male students and research staff Brazil	The successful implementation of a protocol for EEG alpha rhythm detection with the aid of a portable device was achieved.
Shan, Yang, Zhou & Chang (2018)	Human-building interaction under various indoor temperatures through neural-signal electroencephalogram (EEG) methods	22 university students Singapore University	EEG asymmetrical activities can be used as a more objective metric to corroborate traditional subjective questionnaire-based methods and task-based methods.
Wang, Gwizdka & Chaovalitwongse (2016)	Using Wireless EEG Signals to Assess Memory Workload in the <i>n</i> -Back Task	Nine university students (5 m; 4 f) Rutgers University, USA	The wirelessly collected EEG signals appear to be useful in measuring brain activity changes associated with different working memory levels.

I.2.1 Brainwaves as proxy for 'enhanced cognition' state

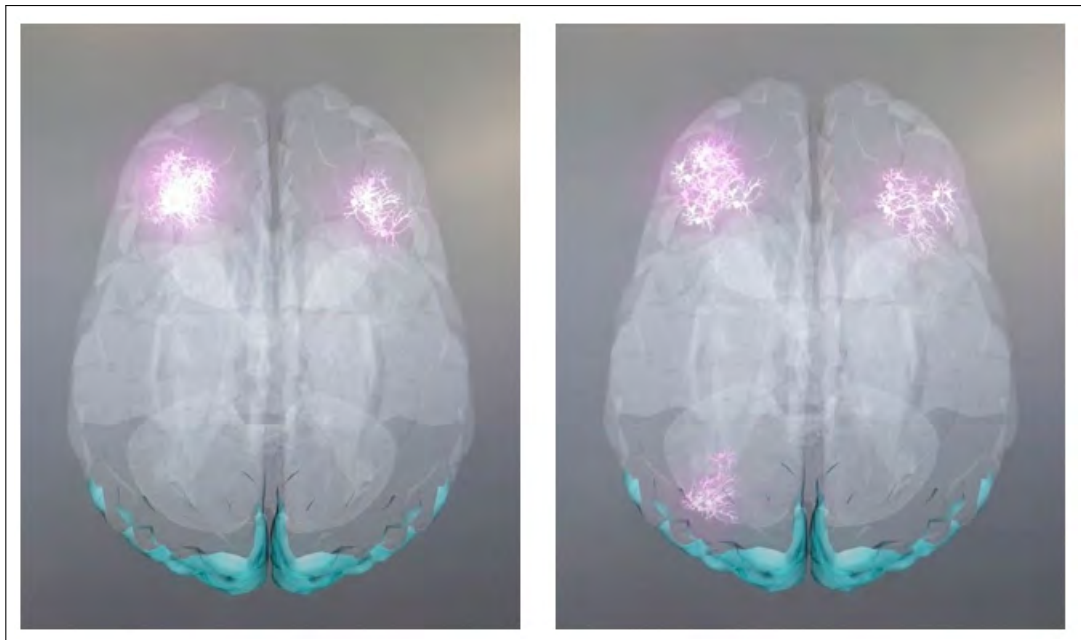
According to Boksem, Meijman and Lorist (2005), when people become fatigued, they generally report difficulties in concentrating and focussing on the required tasks. Under decreased alertness, there is a progressive increase in alpha activity (Sauseng et al., 2005), probably reflecting a decrease in cortical activation (Klimesch, 1997; Staudt and Neubauer, 2006). Consequently, alpha and beta brain waves become synonymous with concentration and cognition. Therefore, to assess the efficacy of

any particular set of environmental parameters, measurement of alpha and beta brain waves is a proxy to establish an 'enhanced cognition' state in a research subject. This review suggests that EEG could be suitable for research in the built environment.

I.3 3D brain visualisation

An essential part of this research was visualising, if any, the cognitive changes in beta brain waves that can occur under different environmental conditions in a primary school classroom. **Figure I.2** shows an example of this. The pink lines are active beta brain waves that change between the two images. These are photos from the video taken during the participant's study. The blue area at the bottom of the picture is the cerebellum and does not change. It is anticipated that as the classroom environment changes and the participant is not as actively engaged, the beta brainwaves will shift in frequency. This outcome cannot be captured without access to real-time 3D imaging software to the brain. This research can do this. The research will also collect raw EEG waveforms that can be analysed, but that is beyond the scope of this research.

FIGURE I.2: *Change in 3D Brain Images (Pink Beta Brainwaves)*



Source: Authors own

I.4 Future research

During the study, the PI was unfortunately unable to conduct any EEG studies with children in school settings due to the heightened ethical regulations imposed by COVID-19. However, several contacts were established towards the latter part of the research, and upcoming research initiatives are now in the pipeline.

1. **Professor Franck Lucas** (Education Manager, Degree in Renewable Energy and Energy Management GEPASUD Laboratory University of French Polynesia)

- The PI and Franck made contact in 2023 in Denmark at the AIVC conference. Franck's feedback to Dr. Boulic on 6th Oct 2023 - *"I met Lara here and I discussed cognitive tests with her... and that I am extremely convinced that our project is very innovative and absolutely must be carried out..."*
- The PI worked with Massey University, the University of French Polynesia, and La Rochelle University in a collaborative effort to create a funding proposal for the Pacific Fund 2024, a joint initiative between French Polynesia and NZ.
 - "Passive cooling of Polynesian schools in a context of climate change: thermal comfort, air quality, cognitive health and reduction of electrical consumption". TROPIC - Thermal Research fOr Pacific Island Classrooms
 - In April 2024, the group received notification that their application had been unsuccessful.

2. Professor Lucas presented the proposed research at the International Building Performance Simulation Association (IBPSA) Conference. For more details, refer to **Figure I.3**.

FIGURE I.3: *Projet TROPIC pour l'étude du rafraîchissement passif des écoles polynésiennes dans un contexte de changement climatique : confort thermique, qualité de l'air, santé cognitive et réduction des consommations électriques*

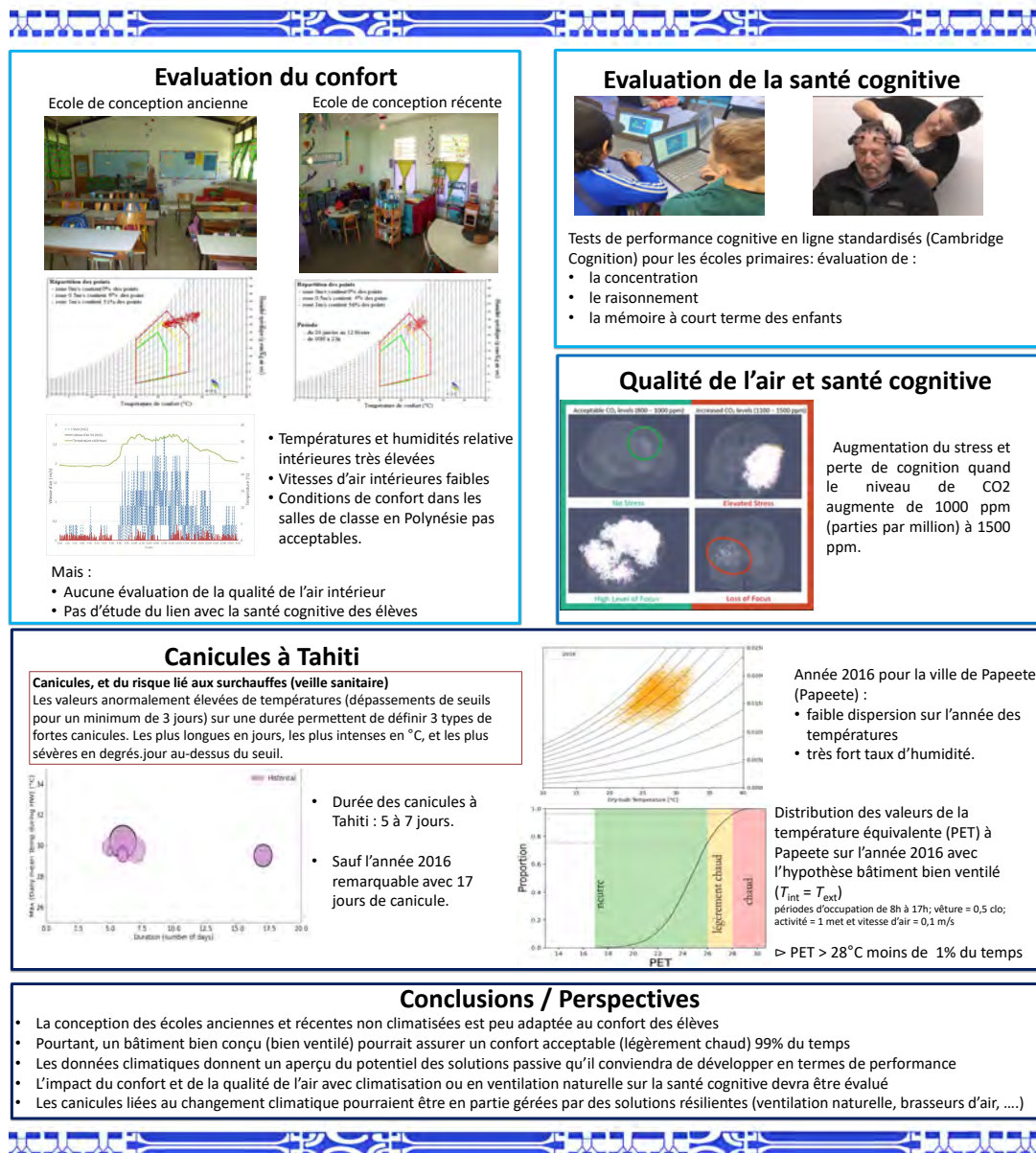


Conférence IBPSA France 2024
13 - 17 mai 2024, La Rochelle / Oléron



Projet TROPIC pour l'étude du rafraîchissement passif des écoles polynésiennes dans un contexte de changement climatique : confort thermique, qualité de l'air, santé cognitive et réduction des consommations électriques

Franck Lucas¹, Emmanuel Bozonnet², Mikael Boulic³, Virgile Lodzinski²



Conclusions / Perspectives

- La conception des écoles anciennes et récentes est peu adaptée au confort des élèves
- Pourtant, un bâtiment bien conçu (bien ventilé) pourrait assurer un confort acceptable (légèrement chaud) 99% du temps
- Les données climatiques donnent un aperçu du potentiel des solutions passive qu'il conviendra de développer en termes de performance
- L'impact du confort et de la qualité de l'air avec climatisation ou en ventilation naturelle sur la santé cognitive devra être évalué
- Les canicules liées au changement climatique pourraient être en partie gérées par des solutions résilientes (ventilation naturelle, brasseurs d'air, ...)

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3. **Professor François Garde** (Professor in Building Physics at University of La Réunion)

- Discussions have commenced to collaborate with Professor François Garde on conducting the research in La Réunion.
- The PI will join the working group to develop a proposal for the AAP RDI project in September 2024.

4. The PI is **assisting two French interns** from The École Nationale des Travaux Publics de l'État or ENTPE to conduct online cognitive and EEG studies on adult participants within an environmental chamber. The TC will be kept constant, but CO₂ levels will be varied between 400 ppm, 1000 ppm, 2000 ppm, and 3000 ppm before returning to 400 ppm after rapidly flushing the room.