Indoor Air Quality and Cognitive Health
A Study in the Tropics

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Interdisciplinary Graduate School

Energy Research Institute @ NTU

2022

Dedicated to my parents

Manjula Devi & Arikrishnan

Without whom this isn't possible

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A thesis submitted to the Nanyang Technological University in partial fulfilment of the requirement for the degree of Doctor of Philosophy

2022

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

20th August 2021

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Date

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20th August 2021

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The contributions of the co-authors are as follows:

- I prepared the manuscript drafts. The manuscript was revised by Assoc.Prof Wan Man Pun, Dr.Adam Charles Roberts and feedback by Asst.Prof Ng Bing Feng
- I designed the study and performed all experimental and preparation work including administrating the protocols. Dr Adam Charles Roberts assisted in administrating the experiment so I can prepare the samples. I am also analysed all the data with guidance from Dr Adam Charles Roberts.
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- Dr Adam Charles Roberts gave insights about the EEG raw data analysis and checked for conceptual error and guided the structure for the discussion.
- I designed the study and performed all experimental and preparation work including administrating the protocols. Dr Adam Charles Roberts assisted in administrating the experiment so I can prepare the samples. I have analysed all the data with guidance from Dr Adam Charles Roberts.

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Nomenclature

Acronyms/Abbreviations

ACH	Air Change per Hour
CO_2	Carbon Dioxide
$PM_{2.5}$	Particulate Matter of aerodynamic diameter of 2.5μm and smaller
IAQ	Indoor air quality
TVOC	Total Volatile Organic Compound
WHO	World Health Organisation
VOCs	Volatile Organic Compounds
EF	Executive Function

Units

ppb	Parts per billion
ppm	Parts per million
$\mu g/m^3$	Micrograms per cubic meters
μm	Micrometers
cfu/m^3	Colony forming unit per cubic meters

Executive Summary

Extensive studies suggest that poor indoor air quality (IAQ) could adversely affect occupants' health, such as sick building syndrome. However, relatively little is known about the impact of IAQ on occupants' cognitive performance. Hence this study aims to examine the correlation between IAQ and the cognitive performance of occupants.

The study adopted a single-blind experimental design to include repeated measures of cognitive function on the same individual with once-a-week exposure over 7 weeks per round in an environmental chamber. Each week was dedicated to an IAQ condition. IAQ parameters include carbon dioxide (CO_2), carbon monoxide (CO), total volatile organic compounds (TVOC), particulate matter ($PM_{2.5}$), formaldehyde, ambient temperature, relative humidity, bacteria count levels, fungi count levels, and ozone (O_3) were monitored. The controlled exposure was achieved by employing particulate filters and molecular filters whilst changing the rate of fresh air intake to manipulate $PM_{2.5}$, TVOC, and CO_2 (bio-effluent), respectively. The environmental chamber was designed to mimic an office environment equipped with a working desk, chairs, desktop, a set of Lego bricks, an EEG headset, disposable earplugs, a mineral water bottle, and an activities instruction sheet.

The study concluded with 90 adult participants (21-35 years of age) over 3 rounds of 7 weeks. The first week of each round was used to familiarise the participants with experimental protocols and the task administered. The full-day (8 hours) experiment is divided into morning and afternoon sessions with lunch (control). The morning session involves a series of activities ending with the test of creativity by employing Serious Brick Play (chapter 4). In the afternoon, participants were assigned a series of activities followed by a power nap, calibration of EEG headsets, and completing the study with a cognitive test battery (PEBL) in one seating. The cognitive test battery comprises 13 tasks that examine the executive functions (EFs) domains; working memory, inhibitory control (attention and response inhibition), cognitive flexibility& control (creativity), speed of information processing, planning, and fluid intelligence (reasoning and problem-solving). The sampling of the electrophysiological responses was administered for the first 30 minutes of the cognitive test battery (Chapter 6).

Participants then remove the headset and continue to complete the rest of the tasks in the battery (Chapter 5).

The key findings of this thesis showed that better IAQ (low levels of IAQ pollutants) improves cognitive abilities. EF domains such as creativity (affected by variation in TVOC levels) are shown to improve by 10.8%, planning (affected by variation in CO_2 levels) is shown to improve by 25.8%, and speed of information processing (affected by variation in $PM_{2.5}$ levels) is shown to improve by 272.7ms and were found to be correlated to one pollutant instead of multiple. By the individual IAQ pollutants. Working memory, cognitive flexibility & control, attention, inhibitory control, and fluid intelligence were observed to have shared influences from $PM_{2.5}$, CO_2 and TVOC levels. These associations were further explained by using 3 engagement indices from the study of electrophysiological responses. The short-term exposure to increasing levels of $PM_{2.5}$ increases cognitive stress that affects working memory related to anxiety. The short-term exposure to increasing levels of TVOC (possibly due to the high concentration of styrene) increases mental effort. This is evidenced by the delay in reaction time and potentially affects the cognitive flexibility & control domain. However, the influence on creativity has not been fully understood. The short-term exposure to increasing levels of CO_2 (bio-effluent) increases the perceived complexity of a task, which influences the planning and attention EF domains.

In summary, using filters targeting specific IAQ pollutants to reduce the overall IAQ pollutant concentration in the enclosed area, such as offices, has shown significant improvement in the productivity of occupants. Specifically, PM filtration has benefited the occupant culminating in; increased attention span and speed of information processing, cognitive flexibility & control, fluid intelligence, working memory, and response inhibition. Carbon filtration has benefited the occupant by positively influencing fluid intelligence, working memory, response inhibition, cognitive flexibility & control, and creativity. The combination of PM and carbon filtration brings collective benefit to all EF, with marginal difference observed between the pollutant dedicated filtration and the combined filtration. The economic benefit of increasing performance and productivity for a company of 400 employees working for 270 days over 10 years being exposed to IAQ conditions with PM and carbon filtrations is calculated to increase performance revenue by 18.5%. This is based on the minimum daily wage, S$23/hr of a professional.

Chapter 1

Introduction

This chapter provides a detailed description of the societal impact from which the work has been developed as well as highlighting the motivation and the main objective and scope of the PhD project. The thesis outline and a summary of each chapter is provided at the end of this chapter.

1.1 Thesis Statement

The study investigates the effects of indoor air quality (IAQ) on human cognition and brain responses. The longitudinal study design comprises 3 rounds of randomised single-blind controlled exposure to different aspects of IAQ. The effects of the controlled conditions were assessed through human responses (psychological and physiological) through repeated measures of play, computerised test battery, and electroencephalography (EEG) testing on the same individuals over 6 weeks (8 hours a day in the week). NTU-Institutional Review Board, IRB-2017-06-014 approved the study, and all participants signed an informed consent document before administrating the study and were compensated upon completing the study.

1.2 Background

1.2.1 Societal Impact

Air pollution is one of the significant environmental threats to human health (IQAir, 2020; WHO, 2018). In the recent years, on a global scale, daily, 9 out of 10 people are exposed to polluted air, which has led to 7 million premature deaths recorded per year (more than 3 times higher than deaths associated with COVID-19), with an estimated welfare loss of US$5 trillion (Aranda, 2019; Kurohi, 2019; Law, 2021). In 2019, World Health Organisation (WHO) reported that 99% of the population worldwide was living in locations where air quality exceeds WHO guideline limits. Predominately in the South-East Asia (SEA) region, annual mean levels (typically based on particulate matter (PM) pollution) exceeded 5 times WHO guideline limits (WHO, 2021a). As a result, more deaths were recorded in SEA than globally due to air pollution. The World Air Quality Report (2020) states that 37 out of 40 most polluted cities are from the SEA region, with 3.2 million deaths recorded, representing the third-highest risk for premature death and the ninth-highest cause in Western Europe. Consequently, in 2020 the total economic cost of US$82.4 billion from 11 megacities in Asia was reported due to air pollution (Board, 2021). Clearly, it indicates the adversity of poor air quality in SEA and the impact on people health and its economy.

Air pollution is an accumulation of indoor and ambient air pollution. Studies on human exposure to indoor pollution showed that the indoor environment could be 2 to 5 times as polluted as the ambient environment (European Comission, 2003). Modern buildings are built airtight for energy efficiency. Thus, they rely entirely on mechanical ventilation to recirculate indoor air with limited ambient air dilution, accumulating indoor air pollutants, making it worse than ambient air pollution (Holgate, 2017). The total time spent outdoors is increasingly insignificant in reference to current urban lifestyles, where people spend more than 90% of their time indoors (Y. Zhang, 2004). At the global level, WHO estimated that 3.8 million people die prematurely from illnesses caused by poor IAQ, such as pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease, and lung cancer (WHO, 2021b). In 2015, among the 3.2 million death recorded in SEA, 55.9% (refer to Figure 1-1) were due to indoor pollution (Landrigan et al., 2017; World Health Organization, 2016). It is noteworthy that the statistics reported for morbidity and mortality in SEA were mainly driven by household air pollution from solid fuels for cooking, heating and lighting.

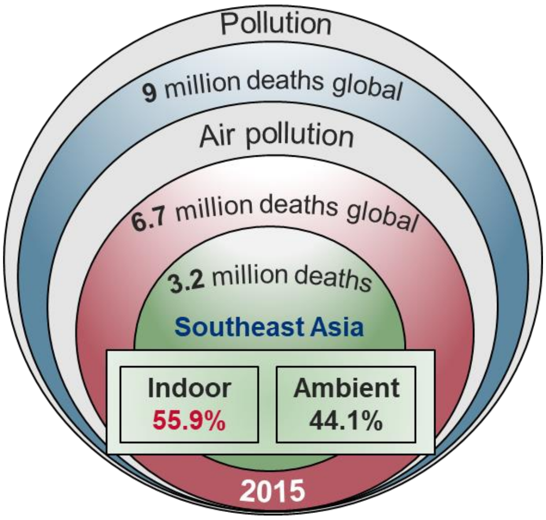


Figure 1-1. An illustration of the premature death counts caused by air pollution in Southeast Asia from a global perspective was reported in 2015. Data was obtained from Landrigan et al. (2017) & World Health Organization (2016).

However, considering an average working adult, 97.7% of their life (23 hours and 15 minutes) is spent in an indoor environment daily(Daigler et al., 1991; Klepeis et al., 2001; WHO, 2014). Hence, it is essential not to disregard the economic burden and health problems associated with poor IAQ from other indoor environments such as offices.

Several studies have reported the effects of poor IAQ, such as sick building syndrome (SBS) experienced among occupants, a decrease in employee productivity (reduction of 10-15%), and damage to objects found in libraries and museums (Cincinelli et al., 2016). A recent study reported that the annual expenses based on poor IAQ concerning the loss of productivity, illnesses, sick leaves, and mortality adds up to 20000 million euros (González-Martín et al., 2021). Furthermore, an annual economic burden of US$60 billion was estimated due to SBS symptoms among office workers, which affected workers' productivity (William J. Fisk, 2002).

The fourth industrial revolution is a significant global shift in the economy towards service and knowledge-based sectors, mainly involving desk-bound work in an enclosed environment (Al Horr et al., 2016). The global shift has indicated that 50% of all employees will need to reskill by 2025 (World Economic Forum, 2020). Therefore, high cognitive abilities and productivity are critical to an employee. Furthermore, a 5-year forecast report for labour market evolution ranked creativity, critical thinking, and complex problem-solving skills as the top 3 critical job skills to succeed (Whiting, 2020; World Economic Forum, 2020). In summary, technology adaptation increases the need for high cognitive abilities for productivity. On the other hand, poor IAQ exposes occupants to health risks such as SBS, affecting workers' productivity. However, little is known about what contributes to the decline in productivity and how IAQ could affect human cognitive health.

1.2.2 Motivation

For 4 decades, researchers have been researching the impact of IAQ on occupants. It is well proven that poor IAQ is the cause of occupants experiencing acute health and comfort issues associated with the time spent in the indoor environment (Environmental Protection Agency & Environments Division, 1991). The phenomenon is typically known as SBS. The predominance of SBS is correlated to the lag of proper ventilation rate, which has been reported to decrease occupant productivity significantly. For instance, a recent study showed that if the ventilation rate was increased two-fold, fewer

SBS symptoms were observed, and occupants' performance improved by 1.7% (Wargocki, 2000). In agreement, Jones (1999) claimed that a possible cause of SBS could be the contamination from the indoor air pollutants such as volatile organic compounds (VOCs) present in the ventilation system, particularly in the air filtration system or maintenance ducts. This increases the complexity of unknowns in finding the cure or cause of SBS symptoms. Hence, the ventilation rate could only be addressed in a small proportion of non-specific symptoms (William J Fisk et al., 2009; Vincent et al., 1997). Apart from the low ventilation rate being one of the reasons for the emergence of SBS, psychosocial factors do play a significant role in reporting the SBS symptoms. For example, Letz’s (1990) theoretical framework highlights psychosocial factors observed with the emergence of SBS symptoms, such as increased awareness of chemical hazards in the workplace, changes in work leading to loss of control and stress amongst workers, and extensive media coverage of outbreaks of SBS. Previous studies showed that psychosocial factors increase the risk of SBS symptom reporting (Kivimäki & Kalimo, 1996; Wallace et al., 1993). Therefore, it seems likely that SBS is a multi-factorial aetiology where work stress could be seen as a mediating factor around the environmental symptoms that interact to produce symptoms and discomfort.

Majority of studies that reported SBS symptoms saw effects between ventilation rate and occupant’s productivity (Kosonen & Tan, 2004a; Seppänen et al., 2006; Wargocki, 2000). Several studies reported a similar trend with a 1-3% improvement in participant’s productivity at a ventilation rate of 10 l/s per person (Seppänen et al., 2006). In addition, a decrease in the SBS symptoms was observed when the ventilation rate increased (Park & Yoon, 2011; Sundell, 1994). Despite the compelling evidence presented above, there is a push to cut costs, which reduces the ventilation rate to conserve energy. Recent studies highlighted that increasing ventilation rates above the guidelines, but below 20 l/s per person increased productivity and improved perceived air quality (Seppänen et al., 2006; Wargocki, 2000). Fisk (2000) reported that an improved work efficiency nationally could incur US$12 -125 billion per annum. Studies on office employees in the UK showed that productivity had increased by 20% in good IAQ, equivalent to 135 billion pounds yearly (Clements-Croome, 2015; Croome, 1999). In addition, there is an annual loss of 15 billion pounds in the UK observed on employees who are present but work with reduced productivity (Irvine, 2011). Therefore, increasing the ventilation rate is observed to improve the occupant's health and as well as their productivity.

Some studies identified indoor air pollutants based on available toxicological and epidemiological data and exposure levels causing health concerns. Comparing the list of pollutants identified in the review by A.P. Jones (1999) and the guidelines from the World Health Organisation (WHO) Europe (2010) highlighted common pollutants, namely, Carbon monoxide, Formaldehyde, Nitrogen dioxide, Radon, Particulate matter (PM) and Volatile organic compounds (VOC) covering a broad spectrum of indoor pollutants. The presence of indoor air pollutants is shown to affect occupants' productivity. Wargocki et al. (1999) interventional study that used a 20-year-old carpet to simulate pollution source and kept the ventilation rate at a constant level revealed that reducing the indoor pollution load proved to be an effective means to improve productivity and the well-being of the occupants. Kosonen et al. (2004a), on the other hand, assume that CO_2 concentration is a good indicator of IAQ when bio-effluents are a significant pollution source. A high concentration of CO_2 saw a decline in the performance of the occupants (Myhrvold et al., 1996). Since there is a limited number of studies done considering the carbon dioxide concentration levels indicate the pollution level indoors, the assumption from Kosonen et al.(2004a) could not be verified further. Nonetheless, both studies showed that reduction in pollution levels did increase occupant’s productivity.

Recently, there has been a growing interest in understanding how IAQ affects productivity and other cognitive functions. A pioneering study done by Allen et al. (2016) proved that different IAQ levels experienced affect cognitive functions through a controlled exposure study with VOCs, CO_2, and ventilation rate. The study deduced that low concentration levels of VOCs showed performance in higher-order cognition functions. It is unknown if any filters were used in the mechanical ventilation system during this double-blind study that lasted for 6 days over 2 weeks. However, the study was not comprehensive in investigating the impact of other major indoor pollutants such as particulate matter and occupant’s cognitive performance. The study was based in New York, the USA, where seasonal variations are a way of life. During the winter, heating systems are used instead of air conditioning systems. Therefore, it is unclear which climate the study by Allen et al. (2016) was done. Whereas in the tropical region, people do not experience seasonal variations. In addition, several studies have highlighted that the concentration and occurrence of indoor air pollutants are affected by the season of the year (C. Jiang et al., 2013; Luengas et al., 2015; Rehwagen et al., 2003). Therefore, it is important to understand how IAQ affects people living in the tropics in terms of their cognitive performance.

Most of these studies were done in the USA and pan-European countries, but few studies discuss the IAQ in Southeast Asia and none about cognitive health. Therefore, this thesis takes a hypothesis of investigating the effects of IAQ on cognitive functions in the tropics. Therefore, Singapore, the global cosmopolitan hub with the majority of the facilities built with mechanical ventilation systems, geographically located on the equator (similar weather conditions of a tropical country), and diverse nationalities make it a suitable location to testbed the hypothesis.

1.3 Objective and Scope

The profound health implications such as lack of productivity and sick building syndrome from short-term exposure to worst IAQ have been well documented; the importance of maintaining good IAQ in enhancing the full cognitive potential in healthy adults (age 21-35 years) is poorly understood in the tropical countries.

The main objective of this thesis is to investigate the association between different aspects of IAQ manipulated with positive intervention and the cognitive performance of the population group in a simulated office environment.

The scope of the thesis is limited to a single-blind study in an environmental chamber (controlled exposure) located at the Nanyang Technological University of Singapore that was designed to simulate a typical office environment. The design of the study models after Allen et al. (2016)'s study design. IAQ was systematically varied in the chamber using filters for different concentration levels of TVOC and $PM_{2.5}$ and adjusting the fresh air intake for different ventilation rates (CO_2 used as a proxy for bio-effluents) over 6 weeks. Each of the weeks was dedicated to an IAQ condition, namely, high ventilation (1 ACH), high ventilation with PM filter, high ventilation with carbon filter, high ventilation with both PM and carbon filter, low ventilation (0.5 ACH), and a repeat of low ventilation (0.5 ACH).

The study was based on 92 recruited student participants spread over 3 rounds of 7 weeks, each between 21 and 35. They were healthy and able to commit for an entire day (8 hours) and were contacted using their university email accounts. Each participant in the study followed a standardised protocol designed specifically to determine cognitive performance. Cognitive performance categorised under specific domains such as creativity, working memory, pattern recognition, response inhibition, speed of information processing, sustained and multiple simultaneous attention, and cognitive flexibility and control are analysed by employing brick play, computerised cognitive test battery, and through measurement of electrophysiological responses.

1.4 Thesis Overview

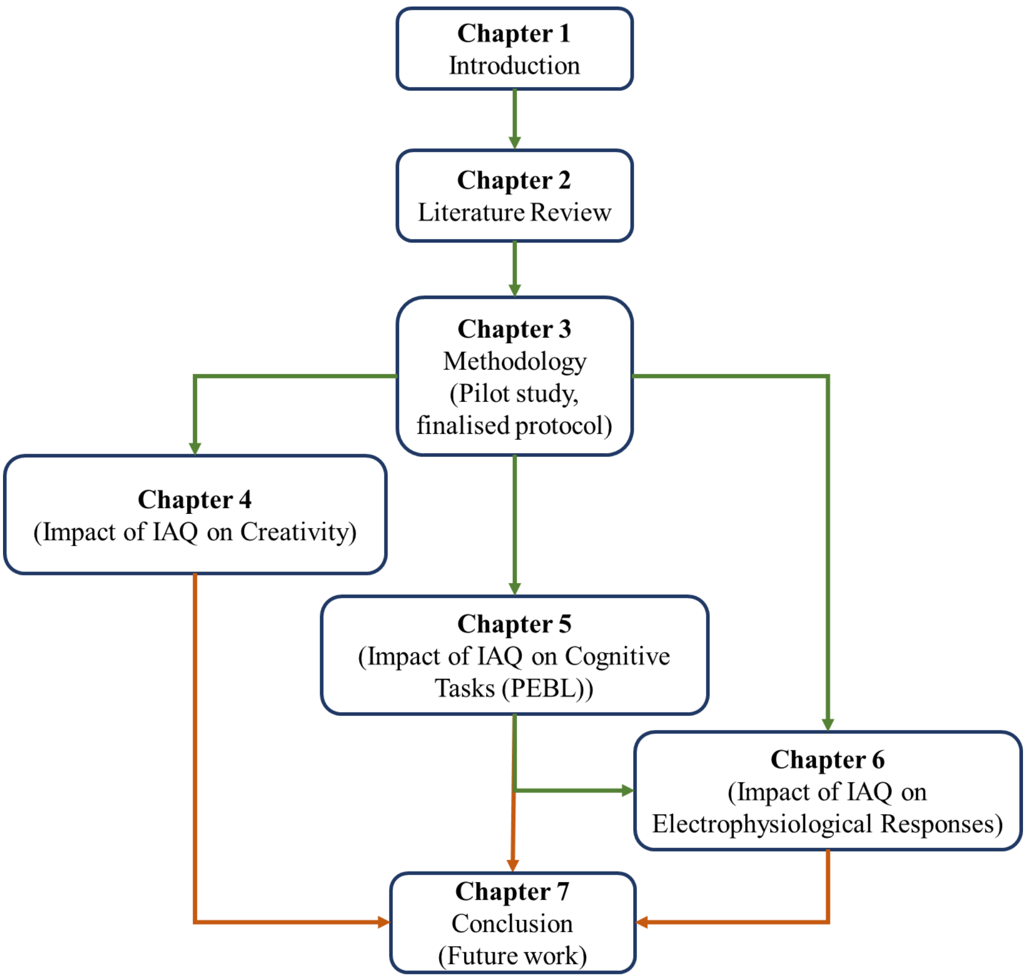


Figure 1-2. A summary flowchart of the thesis structure.

The thesis consists of 7 chapters, as illustrated in Figure 1-2, namely:

- *Chapter 1* provides a rationale for the research taken and outlines the societal importance, motivation, and thesis's main objective and scope.

- *Chapter 2* reviews the literature concerning IAQ parameters ($PM_{2.5}$, VOCs, and CO_2) and the biological pathways in relation to the cognitive influences. The chapter also reviews key models of cognitive performance and the suggested partitioning of the executive functions (EF), and methods of assessing executive functions to understand cognitive abilities and health. Finally, the chapter concludes with a research gap and a proposed structure for EFs.

- *Chapter 3* provides the methodology for two segments. A detailed description of the experimental protocol: description of the experimental manipulation and data sampling. The other is a detailed description of participant protocol. The chapter describes a small-scale pilot study used to test the structure of the participant protocol and details of the final protocol administered.

- *Chapter 4* investigates the impact of IAQ on creativity through play. The key design and consideration, along with data analysis on creativity, are presented in this chapter.

- *Chapter 5* investigates the impact of IAQ on the proposed EF structure through a cognitive test battery. The key design and consideration, along with data analysis on working memory, inhibitory control, cognitive flexibility& control, and higher-order EFs, are presented in this chapter.

- *Chapter 6* investigates the impact of IAQ on electrophysiological responses through electroencephalography (EEG) testing. The key design and considerations, along with data analysis on electrophysiological responses, are presented in this chapter.

The chapter serves mainly as data exploration to understand the underlying biological mechanisms of IAQ on cognitive health.

- *Chapter 7* presents the main conclusions of the thesis by summarizing the results and answering the research questions presented in chapter 2. The chapter highlights the possible impact and limitations and further improvements for future development.

1.5 Original Contribution

The essential research outcomes of the thesis can be summarised in the list below:

- The association of IAQ with creativity by simulating lateral thinking through the adoption of Serious LEGO Play.

- The association of IAQ with cognitive health under the proposed structure of EF domains.

- The association of IAQ with electrophysiological responses by interrelating existing biological mechanisms of IAQ pollutants on cognitive health and psychological theories

Chapter 2

Literature Review and Research Gap

This chapter provides a general and broad literature review regarding the IAQ pollutants, $PM_{2.5}$, TVOC, and CO_2. It also outlines the main conceptual models in defining cognitive performance and partitions of executive cognitive functions. Concludes with the proposing structure for different executive functions, study design based on literatures reviewed, and the research gap that will be answered in Chapters 4, 5, and 6.

2.1 Overview of IAQ Parameters

In recent years, there has been a growing need to understand the effects of IAQ on occupants. In 2010, WHO first established IAQ guidelines on specific indoor air pollutants known for adverse health effects (WHO, 2010). The specific indoor air pollutants include different concentration levels of gases (i.e., not limited to carbon monoxide, carbon dioxide (CO_2), volatile organic compounds (VOCs), formaldehyde, nitrogen dioxide, radon, ozone, and sulphur dioxide), airborne particulate matters (PM) (i.e., PM_{10}, $PM_{2.5}$), and airborne microbial contaminants (i.e., fungi, bacteria) together with environmental condition parameters (air temperature, relative humidity, and air movement). Despite the complexity and number of pollutants present in an indoor environment, measuring a few of them and using them as a proxy to simplify data collection is expected. The proxy compounds are identified by representing similar behaviour of an extended group of compounds or indicating the potential human risk (González-Martín et al., 2021; Jantunen et al., 2011).

PM, volatile organic and inorganic compounds are commonly investigated as indoor air pollutants. VOCs comprises a large group of organic compounds collectively referred to as total volatile organic compound (TVOC) (WHO, 2010). The WHO guidelines and universally reported indicators for IAQ pollution levels are based on $PM_{2.5}$ concentration. Other commonly studied proxy compounds are CO_2, and TVOCs, where short and long term studies have shown adverse effects on human health (Luengas et al., 2015). Previous studies showed that TVOC and $PM_{2.5}$ adversely affect human health, causing sick building syndrome, neurodegenerative illness, and respiratory illness for occupants in the office (Alberts, 1994; Fermo et al., 2021; J. Jiang et al., 2020). Therefore, it is evident that $PM_{2.5}$, TVOC and CO_2 impose risks to human health. The subsequent section elaborates on human health risk potential.

2.1.1 Particulate Matter (PM)

Particulate matter is a broad term used to refer to suspended particles in the air made up of a complex mixture of organic compounds, ions, reactive gases, metals, particle carbon core, pollen, and liquid droplets (EPA, 2016). The suspended particle varies in size and composition, generally classified as PM_{10} (particles with an aerodynamic diameter of 10 μm and smaller) for coarse particles, $PM_{2.5}$ (particles with an aerodynamic diameter of 2.5 μm and smaller) for fine particles and $PM_{0.1}$ (particles with an aerodynamic diameter of 0.1 μm and smaller) for ultrafine particles (EPA, 2016). These particles are small in magnitude and could only be identified under an electron microscope. Due to the small diameters, inhalation of particles can affect the heart and lungs, leading to serious health problems (refer to section 2.1.1.1). Singapore and WHO air quality guidelines state the allowable limit of $PM_{2.5}$ to be 37.5 $\mu g/m^3$ (Singapore Standard Council, 2016) and 25 $\mu g/m^3$ (WHO, 2010) for 24 hours on average.

2.1.1.1 Biological pathway of PM

The upper respiratory tract actively removes the inhaled PM through the clearance mechanisms of the nasal mucociliary (Wanner et al., 1996). However, the clearance mechanisms are ineffective barriers to ultrafine particles (UFP) (Geiser et al., 2005). Previous studies have highlighted 2 main biological pathways of exposure to ambient PM, particularly UFP, as the olfactory and systemic pathways. The olfactory pathway is a direct translocation to the brain via the olfactory nerve. This is due to the UFP deposition in the olfactory mucosa of the nasopharyngeal region (G Oberdörster et al., 2004). A study by Oberdörster et al. (2004) investigated the exposure of UFP through inhalation using rats which showed PM deposits in multiple brain areas, deposited mainly in the olfactory bulb. The study also identified that small particles translocate through the olfactory pathway much faster than big particles. The results revealed (approximated) 100% nasal deposition efficiency for particles below 5 nm diameter and 10% nasal deposition efficiency for particles larger than 30 nm in diameter. This is supported by a pioneering study investigating the transport mechanism via intranasally infusing colloidal gold nanoparticles in squirrel monkeys. The gold nanoparticles were transported through olfactory nerve axons to the olfactory bulbs (De Lorenzo, 2008). The mechanism described above showed that the initial deposition in the olfactory mucosa induces an endocytic uptake through the olfactory rods (retrograde transport within olfactory dendrites and anterograde axonal translocation) and reaches the cells in the olfactory bulb. As a result, the olfactory pathway bypasses the blood-brain barrier (BBB). The same conclusion of particles breaking the BBB and potentially reaching the brain was found in 3 different studies done with young adults at the mean age of

20-25 years, with 2 of the studies using autopsied humans' frontal cortex (Calderón-Garcidueñas et al., 2008) and brain tissue (Maher et al., 2016) and the final study testing the olfactory function of young adults with a mean age of 21, living in extreme air pollution (Calderón-Garcidueñas et al., 2010).

Studies have found that not all UFPs are deposited in the olfactory mucosa. Particles that travel to the lower respiratory tract may reach the brain through the systemic pathway. Several animal studies have found deposits of UFP in extrapulmonary pathways (J. Chen et al., 2006; Kawanaka et al., 2009; Nemmar et al., 2002; Oberdörster et al., 2002). UFPs have unique characteristics such as a stronger inflammatory effect and a large surface area to mass ratio than larger particles that allow UFPs to penetrate the lung tissue. It then travels to epithelial barriers, to peripheral organs and then reaches the central nervous system (CNS) parenchyma (Geiser et al., 2005; Möller et al., 2008; Oberdorster et al., 1992). The inflammatory effect leads to oxidative stress, inducing and eliciting pulmonary inflammation (Hassanvand et al., 2017). In addition, the systemic inflammation from the UFPs increases the permeability of the BBB, which potentially allows efficient entry into the brain tissue (Elwood et al., 2017). However, the transport mechanism through systemic pathways has not been fully understood with human exposure to UFPs, and Table 2-1 summarises the biological pathways from PM inhalation.

Table 2-1. Summary of key biological pathways from PM inhalation

Organs	Biological pathways	References
Lungs	- Inflammation - Oxidative stress - Increased respiratory symptoms - Reduced lung function	(G Oberdörster et al., 2004) (Hassanvand et al., 2017)
Blood	- Altered rheology - Increased coagulability - Translocated particles - Reduced oxygen saturation	(Geiser et al., 2005; Möller et al., 2008; Oberdorster et al., 1992
Heart	- Altered cardiac autonomic function - Increased dysrhythmic susceptibility - Altered cardiac repolarisation - Increased myocardial ischemia	(Craig et al., 2008)
Brain	- Increased cerebrovascular ischemia	(De Lorenzo, 2008) (Maher et al., 2016)

2.1.1.2 Effects of PM on cognition

Long-term longitudinal studies on populations living in highly polluted cities in Mexico and USA showed poor cognitive abilities in terms of memory (Ailshire & Clarke, 2015; Salinas-Rodríguez et al., 2018). However, it is not clear if there was a comparison to people living in less polluted areas for the same duration. A study done over 6 years involving 1496 ageing adults (people close to retirement) found that every increment of 10 $\mu g/m^3$ in $PM_{2.5}$ exposure would accelerate the decline of verbal learning ability due to ageing by 30% (Gatto et al., 2014). Similar findings were reported in another long-term (4 years) exposure study on ageing adults done in China (Xin Zhang et al., 2018). Short-term studies done in China and Singapore by employing air purification of $PM_{2.5}$ over 1 week of reduced exposure observed an improvement in young healthy adults' lung function and a decrease in blood pressure through cardiorespiratory biomarkers (Y. Wang et al., 2021). Hence from the studies above, it is evident that penetration to the lung and affecting its function could potentially break the BBB and deposit it in the brain over time. Thus, prolonged exposure to $PM_{2.5}$ can affect memory and learning abilities, and short-term exposure affects lung function.

2.1.2 Volatile Organic Compounds (VOCs)

Organic compounds comprise volatile organic compounds (VOCs), semi-volatile organic compounds, and non-volatile organic compounds. Indoor VOC sources include consumer and commercial products, paints and associated supplies, adhesives, furnishings, clothing, building materials, combustion appliances, and occupants (Maroni et al., 1995). VOCs emitted from occupants are known as bio-effluents. Bio-effluents are organic compounds emitted by the occupants, including carbonyls, ammonia, aromatic alcohols, alkyl alcohols, and mercaptans (Godish, 1996).

Studies have shown that exposure to VOCs could result in acute and chronic health effects such as depression of the central nervous system and irritation of the eyes and respiratory tract, similar to sick building syndrome (Jones, 1999; Maroni et al., 1995). Due to the nature of VOCs, their concentration will decline rapidly and exponentially as these compounds tend to off-gas a significant proportion of their volume in a relatively short time to the surroundings (Jones, 1999). The most commonly found VOC in office spaces is toluene (Tham et al., 2000). Previous studies investigating the effects of sick building syndrome showed that VOC sources are the main reason for health hazards compared to direct exposure to the VOCs (Wolkoff, 1997). According to SS 554 (Singapore Standard Council, 2016), the allowable limit is 1000 ppb for 8 hours.

2.1.2.1 Biological pathway of VOCs

Excessive exposure to VOCs is associated with short and long-term adverse health effects such as cancer (Mølhave et al., 1997) and CNS disorders (Jumpponen et al., 2013). There are 3 possible routes of VOCs exposures in humans for instance inhalation (respiratory system), dermal absorption (dependent on the transdermal permeability), and consumption (drinking water and diet) (He et al., 2019; Manisalidis et al., 2020; Raffy et al., 2018). Studies have stated that among the 3, the main route of exposure to VOCs is the respiratory system (Gong et al., 2017). The barriers present in the upper respiratory tract to remove pollutants becomes ineffective for VOCs due to their chemical property of low polarity and poor solubility in water (Zhao et al., 2019). Thus, VOCs could quickly move to the lower respiratory tract, to alveoli (Gasparri et al., 2016; Haick et al., 2014). As a result, several epidemiological studies have highlighted the adverse risk to the lungs due to the VOC exposure (Arif & Shah, 2007; Cakmak et al., 2014; Pappas et al., 2000).

The standard methods used to detect VOC exposure are exhaled breath, blood, and urine samples. Filipiak et al. (2013) speculated a plausible transport mechanism of VOCs from the circulating blood to the peripheral vasculature to the alveolar space. Another hypothesis claims that epithelial cells lined the lung surface or tissues that introduce VOCs to the exhaled breath. The lack of knowledge of multiple compounds and their toxicity has made it difficult to explain the causation of VOC exposure (Aufderheide, 2008). However, the exchange of gases in the lungs occurs through passive diffusion of gases between the blood and alveolus in the lung capillaries found in the pulmonary alveoli (Filipiak et al., 2013). In addition, Yoon et al. (2010) found that VOCs impair pulmonary function and increase oxidative stress, this findings has been supported by other studies (Bentayeb et al., 2013; Bönisch et al., 2012). Therefore, VOCs could potentially reach the brain by compromising the integrity of the blood-brain barrier, affecting the CNS by the increment of oxidative stress and neuroinflammation (Butterfield & Kanski, 2001; Gella & Durany, 2009; Thawani et al., 2016). Most of the toxicology studies are based on individual VOCs instead of TVOCs.

Table 2-2. Summary of key biological pathways from VOC inhalation

Organs	Biological pathways	VOC	References
Lungs	- Irritation of the respiratory tract - Alveoli affected - Impaired pulmonary function - Oxidative stress	Nonane	(Rajabi et al., 2020) (He et al., 2019; Manisalidis et al., 2020; Raffy et al., 2018) (Arif & Shah, 2007; Cakmak et al., 2014; Pappas et al., 2000)
Blood	-		
Heart	- Irregular heartbeat	Benzene	(Rajabi et al., 2020)
Brain	- Central nervous system disorders - Neuro inflammation	Styrene Toulene	(Rajabi et al., 2020) (Jumpponen et al., 2013) (Butterfield & Kanski, 2001; Gella & Durany, 2009; Thawani et al., 2016)

2.1.2.2 Effects of TVOC on cognition

Excessive exposure to TVOCs affects the ability to make decisions. For example, a pilot study done by Satish et al. (2013) exposes participants to latex paint for 2 hours. It evaluates the participant's ability to make decisions and productivity after the exposure and 48 hours later by using Strategic Management Simulation (SMS) tool and collecting TVOC data. The study concludes that a significant decrement was reflected when subjects were exposed to high TVOC concentration. Another study was done by Allen et al. (2016) showed a significant reduction in decision-making tasks when the concentration of TVOC was increased. Li et al. (2016) investigated the effects of formaldehyde (organic compound part of the VOC family) inhalation on anxiety-like and depression-like behaviour and cognition. The study concluded that the exposure impaired novel object recognition and increased levels of depression-like behaviour. Therefore, decreasing the TVOC contents indoors will see an increase in cognitive functions, particularly decision making.

2.1.3 Carbon Dioxide (CO_2)

Carbon dioxide is an odourless, colourless, tasteless, non-flammable gas that traps heat. It is a by-product of human cell function (metabolism). The primary source of CO_2 in an indoor environment is human metabolism (Alberts, 1994). Generally, indoor CO_2 concentration is an indicator of air exchange rate suitability, sufficient fresh air within the indoor spaces, and indoor air quality acceptability (Emmerich & Persily, 2001). Singapore Standards Council (2016b) guideline limit for indoor spaces states that an enclosed room must not exceed 700 ppm more than the ambient CO_2 concentration. The average ambient concentration in Singapore is 450 ppm approximately.

2.1.3.1 Biological pathway of CO_2

There are two possible CO_2 exposure pathways; one produced by the human's intracellular metabolism and another inhaled from the environment. The production of CO_2 within the cells is transported to the blood, and the blood carries it through the venous system to reach the lungs, where it is transferred to the alveoli and exhaled (Lifson & Gordon, 1949). The accumulation of CO_2 due to the metabolism rate of a human or inhalation decreases the blood pH, increasing the partial pressure of CO_2. The human body discharges CO_2 to maintain its acid-alkaline equilibrium. Therefore, an increase in partial pressure of CO_2 in the alveoli results in CO_2 diffusing through the alveolar membrane into the bloodstream and disrupting the acid-alkaline equilibrium known as respiratory acidosis (Guais et al., 2011). Previous studies have found that low-level CO_2 exposure (between 400 and 2000 ppm) induces systemic inflammation and worsens intracellular oxidative stress in human neutrophils (Coakley et al., 2002; Jacobson et al., 2019; Zappulla, 2008). A study has shown that respiratory acidosis causes CO_2 to rapidly diffuse into the brain across the BBB, where a high concentration of CO_2 has been found in the CNS (Goldberg et al., 1961).

Table 2-3. Summary of key biological pathways from CO_2 inhalation

Organs	Biological pathways	References
Lungs	-	-
Blood	- Decreased blood pH - Reduced oxygen saturation - Respiratory acidosis	(Lifson & Gordon, 1949) (Guais et al., 2011)

	- Systemic inflammation in neutrophils - Intracellular oxidative stress in neutrophils	(Coakley et al., 2002; Jacobson et al., 2019; Zappulla, 2008)
Heart	-	-
Brain	- Deposits in the central nervous system from respiratory acidosis	(Goldberg et al., 1961)

2.1.3.2 Effects of CO_2 on cognition

At low concentration levels of CO_2, it is usually considered a proxy for occupant generated pollutants (bio-effluents) and for estimating the ventilation rate per occupant (Apte, 2000). Maula et al. (2017) and Petersen et al. (2016) studies reduced the ventilation rates to increase CO_2 concentration levels (540 ppm - 2260 ppm and 900 ppm - 1500 ppm, respectively) and found negative effects on task performance. Conversely, other studies suggested a direct effect of low-level exposure to CO_2 (600 ppm – 3000 ppm) on performance independent of the ventilation rate (Allen et al., 2016a; Kajtár & Herczeg, 2012; Satish et al., 2012). However, strong evidence from Zhang et al. (2017) investigated the effects of exposure to CO_2 and bio-effluents for 255 minutes on 25 young adults at a mean age of 23. The study used three different concentration levels of CO_2 exposure, 500 ppm (baseline), 1000 ppm, and 3000 ppm while ensuring the outdoor air supply rate was high enough to remove bio-effluents (CO_2 was chemically altered). The study also examined metabolic CO_2 (restricting outdoor air supply rate to include bio-effluents) to understand the effects of bio-effluents and CO_2. The study concluded that no statistically significant effect was observed on cognitive performance when pure CO_2 was added in the absence of bio-effluent. Therefore, at low levels of CO_2 concentration, CO_2 is used as a proxy for bio-effluent. In the presence of bio-effluent, statistical significance on cognitive performance was observed in reduced speed and response time. In agreement, a study reported by Maddalena et al. (2015) also found that short-term exposure (4 hours) at low concentration (900 ppm) of CO_2 and increased bio-effluent levels resulted in a significant reduction in cognitive performance of decision-making ability. The study also found a similar conclusion when TVOC increases but CO_2 remained constant at 900 ppm. Similarly, the controlled exposure study from Allen et al. (2016) on 24 participants exposed to different concentration levels of CO_2 (550 ppm, 945 ppm, and 1400 ppm) for 8 hours resulted in a significant decrease in decision-making tests with increasing concentration levels of CO_2. Therefore, both CO_2 and bio-effluents may affect performance.

2.2 Executive Functions

Human cognitive performance employs executive functions (Koutsandréou et al., 2016). Recent studies have shown that the individual differences in executive functions (EF) are related to occupational functioning and job success (Bailey, 2007; Barkley & Fischer, 2011; M. Miller et al., 2012). EFs are the top-down mental processes required when one concentrates and pays attention without relying on instinct, where overall planning, regulation, control and management of cognitive processes are involved. (Burgess & Simons, 2012; Espy, 2004; Lezak et al., 2004; E. K. Miller & Cohen, 2001). EF was conceptualised as abilities of goal formation, planning, administrating goal-directed plans, and effective performance (Jurado & Rosselli, 2007). EF is believed to constitute a wide variety of components. Some studies have tried to model the theories of executive functions and brain organisation in frameworks elaborated in the following sections.

Framework 1:

Working memory defines the capacity to hold and manipulate information while performing a task such as learning, reasoning, and comprehension. Baddeley & Hitch (1974) proposed a model for working memory with 4 subcomponents: phonological loop, visuospatial sketchpad, central executive (controlling system), and episodic buffer. Control is observed when working memory is used for maintaining goals and inhibiting environmental and internal distractions. This corresponds to inhibitory control. The central executive component is a system of attentional control where one can focus and switch attention without the capacity to store it (Baddeley & Logie, 1999). It is poorly specified and has been described as a “homunculus”. According to Baddeley (1998 & 2002), this component of working memory does not reject the subprocesses' functionality that could have been mapped anatomically.

Framework 2:

Norman & Shallice (1986) described the control of information processing, another essential model highlighted in the literature. It was thought that environmental stimuli triggered the selection of routine actions. For non-routine control behaviour, a supervisory attentional system (SAS) was employed. SAS intervenes when routine responses to stimuli are inadequate. This implies that tasks drawing on the central executive / SAS will only receive interference from tasks that cannot be performed automatically.

Framework 3:

Zelazo et al. (1997)'s model conceptualise macrostructure with executive subfunctions in which the combination satisfies the higher-order function of problem-solving. The 4 corresponding executive processes identified are problem representation, planning, execution, and evaluation. Moreover, it allows the identification of failures of executive functioning in a temporal sequence of problem-solving. Hence, it emphasises that complex functions require the integrity of other brain areas (Zelazo & Müller, 2010).

In summary, the hierarchical cognitive models such as Baddeley's working memory model and Normal and Shallice's SAS model support the central executive system related to the complexity of functioning associated with the prefrontal activities in the human brain. Executive functioning is controlled in the prefrontal regions, where multiple neuronal connections to other cortical, subcortical and brainstem areas of the brain. In agreement, Zelazo et al. (1997)'s framework highlighted the need for other brain areas to determine the control of executive functions. Furthermore, since EF involves coordinating complex cognitive processes to achieve a specific goal, it is important to partition the EF to establish a clear distinction between cognitive process and executive control over the processes so that assessment results can be correctly interpreted.

2.2.1 Partitioning the EF

The central executive could be divided into 4 core functions Baddeley (1966) as listed below:

1. Capacity to coordinate performance on 2 separate tasks
2. Capacity to switch strategies from random generation
3. Capacity to attend selectively to a stimulus and inhibit others
4. Capacity to hold and manipulate information in long-term memory

Other attempts to partition the EF were presented by Fuster (1995, 1997, 1999), suggesting that the prefrontal cortex creates a temporal organisation of behaviour and language through its control of four cognitive executive operations as listed below:

1. Motor working memory
2. Perceptual working memory
3. Attention and motivation
4. Inhibitory control

Faw's (2003) executive committee theory follows a similar functional anatomy approach of using pathological evidence and suggests 5 sub-committees: perceiver, verbaliser, motivator, attender, and coordinator. The interactions produce 6 EFs as follows below:

1. Perception
2. Working memory
3. Attention
4. Long-term memory
5. Motor control
6. Thinking

These sub-committees in this model are similar to mapping the associated areas in the cortex (Jackson, 1915). Jackson's (1915) mental processes in these areas include interpretation of sensory information, the association of perceptions with previous experience, focussing on attention, and exploring the environment.

Therefore, according to Miyake et al. (2000), there are 3 core (clearly distinguishable yet sharing some commonality) EFs: inhibition (defined as controlling one’s attention or thoughts to override a strong tendency), working memory, and cognitive flexibility (defines as the flexibility to adjust, change, and switch between rules, perspectives, and approaches). An extension of the core is higher-order EF, such as fluid intelligence (defined as the ability to identify patterns and solve problems which share domains with reasoning and problem solving (Salthouse et al., 2003)) and planning (Collins & Koechlin, 2012) which are primarily dependent on the frontal lobes (Goel et al., 1997; Tranel et al., 1994). These form the partitions of EF.

2.3 Methods of Assessing EF

Assessing the complexity of the real-world environment is challenging due to the presence of environmental disturbances that could be difficult to model. Hence, a computer-based simulation of a complex, automated working environment is perceived as a more viable alternative for combining the controllability of the experiment with external validity. Such simulation shares a high level of complexity, dynamic where time is a critical variable, and an opaque system to enable inferences from the information. Therefore, it is important to understand the environmental stimuli that model the complexity to understand the real-world environment complexity. According to Steimer (2002), human response to environmental stimuli can be classified into behavioural, psychological, and physiological. Behavioural response is associated with the individual’s actions, mannerisms, or habitual gestures.

Psychological responses are functional processes related to an individual's mental and emotional state. The psychological response is assessed through traditional and automated methods. The traditional assessment method used to measure EF is through qualitative sources of information such as questionnaires as a self-report variable specially designed to test different parts of the cognition ability, perceived IAQ and sick building syndrome. However, these questionnaires are not standardised, which means that often the measures are not comparable between studies (Jones, 1999). The traditional methods also lead to perception biases and raise criticisms about reliability and precision. The automated assessment method uses a computer interface to use an automated neuropsychological test battery. For instance, Allen et al. (2016) and Satish et al. (2013) introduced strategic management simulation (SMS) software to assess the cognitive function among the test subjects, which involved simulation scenarios as a computer-based task. Another widely used software is Cambridge Neuropsychological Test Automated Battery (CANTAB). CANTAB is a computer-administered set of tests focusing on specific cognitive components.

Similarly, The Psychology Experiment Building Language (PEBL) test battery is also a computer-administered test battery that is a well-documented open software (Mueller & Piper, 2014). The cognitive testing requires the participants to have basic computer working skills. The test battery consists of 96 tasks targeting different EFs. From comparing the strengths and limitations of the automated assessment (summarised in Table 2-4), PEBL outweighs the flexibility to select the appropriate task relevant to the research hypothesis and create a battery to be administered.

Table 2-4. Summary of strengths and limitations of automated assessment

Test battery	Strength	Limitation
SMS (Allen et al., 2016a)	Objective assessment tool Validated	Restricted to Harvard research group
CANTAB (Sahakian et al., 1992)	Validated Recognised as an international gold standard Suitable for CNS, neurology & psychiatry research Test difficulty is adjusted to cater to all ages and abilities	Subscriptions required Predefined test Limited use on computing platforms Multiple test variants
PEBL (Mueller & Piper, 2014)	Validated User friendly Allows to design for experiment or defaults modes Use on multiple computing platforms Used in clinical assessment	Open source

Physiological response refers to responses of the bodily parts to the stimulus without any extra effort from the individual (Elliott & Quintino, 2018). Physiological effects are measured using biometric sensors such as heart rate, blood sample, urine samples, and EEG (electroencephalogram) (Filipiak et al., 2013; Nkurikiyeyezu et al., 2019).

Typically, previous studies only use one type of assessment to conclude to answer the research question. Most of the studies tend to stick to the traditional assessment methods to determine psychological responses and draw a strong conclusion. The type of assessment implemented varies from study to study with no standardisation. The findings reported from such studies are questionable. There could be several factors in the traditional methods influencing the data, such as participant's perception, misunderstanding of the questionnaires, and guessing the answer.
In contrast, physiological responses make it difficult to challenge the outcome. This is because the responses are based on the bodily parts of the individual, where it is almost impossible to self-manipulate the outcome. Implementing more than one assessment

method removes the ambiguity and chance finding. For example, a recent study that used more than one assessment method investigated the relationship between thermal comfort and different indoor temperatures through EEG measurements and questionnaires (Shan & Yang, 2020). Additionally, previous studies that used EEG measurements also implemented subjective questionnaires to study the effects of sleep quality and thermal comfort (Lan et al., 2014; Yao et al., 2008).

Cognitive functions are assessed based on independent tests on brain functions, computerised test batteries, questionnaires, and toxicology analysis. In comparison, EEG is a method to record electrical activity on the scalp that represents the macroscopic activity of the brain (Kane et al., 2017). Previous studies have shown that EEG signals could assess cognitive functions (Al-Nuaimi et al., 2021; Besthorn et al., 1995; Sridhar & Manian, 2020). In addition, studies have also shown that EEG signals can capture small changes in alertness, attention, and workload (Berka et al., 2005; Makeig & Inlow, 1993; Prinzel et al., 2003). A recent study (McWilliams et al., 2021) assessed the feasibility of repeated assessment of cognitive functions such as decision making, executive function, and memory in 89 healthy adults using a tablet application (gamified cognitive and passive task) and 16 channels dry-sensor EEG wireless headset. The home sessions were performed 5 times a week for 12 weeks, and each lasted for 30 minutes. The study concluded that the findings from the home sessions replicated well with the lab sessions for the same cognitive domains assessed. Hence, continuous EEG monitoring is robust, sensitive, unobtrusive to participants' performance, has good time resolution to capture changes in mental status or cognitive impairments, and is cheap to deploy.

2.4 Research Questions

Previous studies have indicated that short-term exposure to pollution, which includes low pollution levels, has been reported to cause death (Di et al., 2017; Schwartz et al., 2017; Shi et al., 2016). The Environmental Protection Agency (EPA) has reported that fine particles pollution ($PM_{2.5}$) poses harm to the human nervous system, such as reduced brain volume and cognitive effects (EPA, 2019). Hence, this indicates the impact of short-term pollutant exposure on cognitive performance. Furthermore, it is evident from the literature that poor IAQ indicates sick building syndrome and low productivity among occupants. Studies that showed a high concentration of $PM_{2.5}$ affects cognition were based on long term exposure of 4-6 years (section 2.1.1.2). Despite $PM_{2.5}$ being one of the primary air pollutants for high death rates, Allen et al. (2016)'s experiment design did not examine the possible effects of $PM_{2.5}$ on cognition. Studies that examined the effects of long-term exposure to a high concentration of $PM_{2.5}$ pollution, mainly from high traffic zones, affected memory and learning abilities (Ailshire & Clarke, 2015; Gatto et al., 2014; Salinas-Rodríguez et al., 2018; Xin Zhang et al., 2018). These studies did not examine the short-term effects of exposure to $PM_{2.5}$ during the years of study. Instead, the effect was examined at the end of the exposure years. Furthermore, the studies were based on natural ventilation instead of mechanical ventilation. The target participant in these studies were ageing adults who are highly vulnerable to health issues. Since there are several missing gaps, it makes it difficult to conclude that IAQ with mechanical ventilation will have the same effects on memory and learning abilities being affected with short-term exposure.

However, in a less polluted indoor environment, a short term study examining the effects of air-purifier on IAQ for one week showed changes in lung function (Y. Wang et al., 2021). This indicates that $PM_{2.5}$ pollution is not a long-term effect. Instead, short-term exposure shows significant changes in participants. The study was done on young working adults instead of ageing adults. The study did not further examine what other abilities (such as cognitive functions) could have been affected by the changes observed in lung function. Several studies investigating the effects of a high concentration of TVOC on human cognition found that the ability to make decisions was affected. A commonality observed in these studies was the introduction of sources such as whiteboard markers, latex paint, and glue sticks, to name a few, to increase the concentration of TVOC rather than understanding the potential effects from a typical environment without the need for source introduction. Even though Allen et al. (2016) introduced office supplies as the source for the simulated office environment, it is rare to have the same quantity of supplies exposed in an office every day. Hence, it is unrealistic to introduce sources that do not simulate the typical day-to-day environment. Literature that studied the effects of low concentration of CO_2 showed similar outcomes when participants were exposed to a high concentration of TVOC. Previous studies identified that at low concentrations of CO_2, the effects are contributed mainly by bio-effluents (Godish, 1996; Maddalena et al., 2015; Wyon, 2005; X. Zhang, Wargocki, Lian, et al., 2017). An important finding discovered by Zhang et al. (2017) showed that pumping in pure CO_2 after removing bio-effluents to increase the concentration of CO_2 in the environment did not significantly affect cognitive performance. However, in Allen et al. (2016)'s study, pure CO_2 gas was used to increase the concentration of CO_2 and reported a significant effect on decision-making ability at a high concentration of CO_2. The effects of bio-effluents nor the removal of bio-effluents were not reported in Allen et al. (2016) findings when pure CO_2 gas was utilised to increase the concentration in one of the conditions.

Several studies have proved it (see section 2.1.1), investigating the mechanisms of the biological pathway due to $PM_{2.5}$ exposure reaching the human brain and the health effects it causes. However, the exposure effects of $PM_{2.5}$ on occupants are generally investigated as a long-term (minimum 3 months) study. As a result, there is a poor understanding of the short-term exposure effects of $PM_{2.5}$ on occupants. While some studies examining the effects of VOCs has been well documented for short-term exposure, from the literature, it is evident that both $PM_{2.5}$ and VOCs pollutants share similar biological pathways to reach the human brain. Thus, indicating that exposure to $PM_{2.5}$ may have short-term exposure effects on occupants. Furthermore, the association between IAQ and cognitive function suggested by these studies (section 2.1) leads to the hypothesis that IAQ and creativity could also be associated. Therefore, it is inevitable that none has examined the possible effects of IAQ on cognitive health of working adults (21-35 years of age) in terms of executive cognitive functions in tropical countries focusing on PM2.5, TVOC, and CO_2 (bio-effluents).

Given the complexity and the less defined partitioning of the cognitive functions, I propose the structure for the executive functions illustrated in Figure 2-1. In addition, the tasks selected from the pool of tasks available in PEBL to create a test battery was crossed referenced with CANTAB test batteries and PEBL manual (Fray et al., 1996; Mueller, 2010) to complement the structure in Figure 2-1.

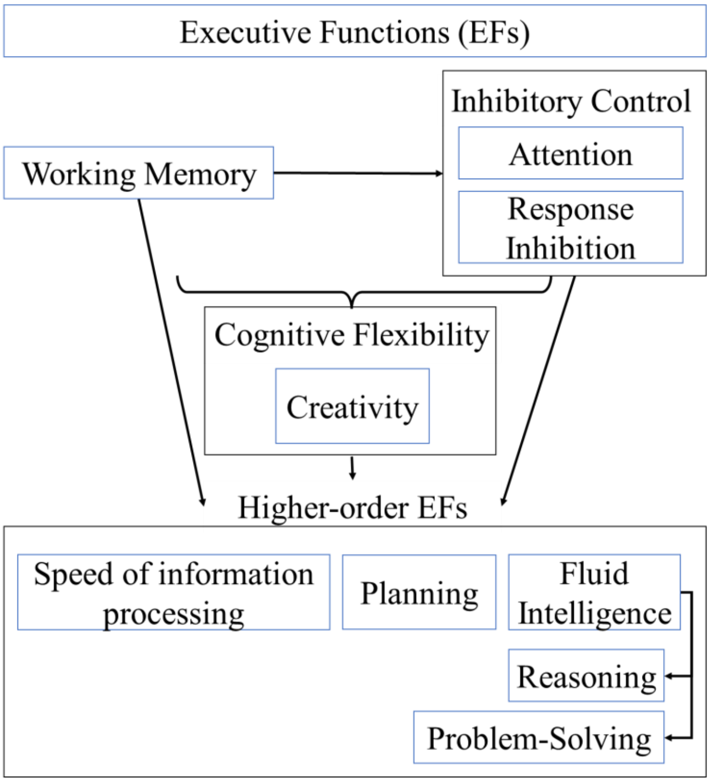


Figure 2-1. Adapted from (Diamond, 2013) and modified accordingly to suit the experimental design of this study.

This thesis proposes modelling closely to Allen et al. (2016) study methodology as an experiment design skeleton based on the literature reviewed. It modifies it accordingly to examine possible cognitive factors behind Allen et al. (2016) results. Furthermore, to enhance the reliability and precision of the data obtained, the study explores 3 different ways of obtaining the data: play, PEBL test battery, and physiological measurement from the participants. Finally, combing all aspects discussed above, the thesis attempts to answer the research gap in the following 3 areas:

1. The impact of IAQ pollutants ($PM_{2.5}$, TVOC, and CO_2) on creativity. (Chapter 4)
2. The impact of IAQ pollutants ($PM_{2.5}$, TVOC, and CO_2) on cognitive performance was examined through PEBL test battery. (Chapter 5)
3. The impact of IAQ pollutants ($PM_{2.5}$, TVOC, and CO_2) on cognitive performance through electrophysiological Responses. (Chapter 6)

Chapter 3

Methodology

The chapter describes the methodology used to design the experimental study that extends over Chapters 4, 5 and 6. The skeleton of the methodology was based upon Allen et al. (2016) study methodology. The adopted methodology was elaborated based on the study's research questions and constraints. The chapter provides an extensive description of the controlled exposure, study protocol, participant protocol (derived from a pilot study), and statistical models used to analyse the raw data in Chapters 4, 5, and 6 and concludes with the summary of the IAQ parameters ($PM_{2.5}$, TVOC, and CO_2) used in the analysis.

3.1 Overview

The experimental design consists of 3 main components, study setup, study protocol, and participant protocol. The study setup includes the environmental chamber and study conditions. The study protocol highlights the details of environmental monitoring. Whereas, the participant protocol includes participant recruitment, participant demographics, participant's study schedule and daily protocol. The feasibility and robustness of the sequence of activities presented in the daily protocol were determined by a pilot study. The statistical analysis was done to understand the interaction between the main components (environmental setup and protocol administered) and the concentration levels of IAQ parameters obtained from the study.

3.2 Study Setup

3.2.1 Environmental Chamber

The environmental chamber, as shown in Figure 3-1, used for the study was constructed and furnished with internal dimensions of 9 m (L) × 3 m (W) × 2.4 m (H), located in the basement of a laboratory building at the Nanyang Technological University of Singapore. The chamber's side walls were constructed with 12-mm-thick calcium silicate broads and rock wool insulation. The wall surfaces were painted in white colour (emulsion paint). The concrete flooring of the chamber was covered with nylon carpet tiles. Dimmable LED lighting fixtures covered the ceiling entirely. On one of the longitudinal sides of the chamber, two flat-screen LCD TVs covered with roller window blinds with a spring chain system were installed to mimic the presence of windows (to reduce the feeling of confinement). The internal space of the chamber was furnished to resemble a typical office-like environment with six working desks. Each desk was equipped with a desktop computer, LEGO bricks, EEG headsets, a list of micro activity instructions, and provided a pair of earplugs and a Dasani mineral water bottle.

The configuration of the chamber is symmetrical in the longer side direction. The chamber was served by two individual air-conditioning and mechanical ventilation (ACMV) systems in a symmetric arrangement. On each half of the chamber, conditioned air was provided by a fan coil unit (FCU) having a cooling capacity of 1.5 kW and a constant volumetric flow rate of 150 L/s through an air diffuser and a return air grill on the shorter side wall. The air in the chamber was circulated by a circulating air loop driven by a fan having a volumetric capacity of 1000 L/s controlled by a variable speed drive. Each circulating air loop had a fresh air intake with an adjustable damper to allow ventilation rate adjustment. A filter box with three filter slots allowed for a maximum of two PM filters and a carbon filter to be fitted. By fitting different filters into the filter box, PM and TVOC concentration levels in the chamber could be varied. The fan speed was varied to compensate for the different pressure drops due to the insertion of filters such that the circulation rate remained constant at 300 L/s throughout the study.

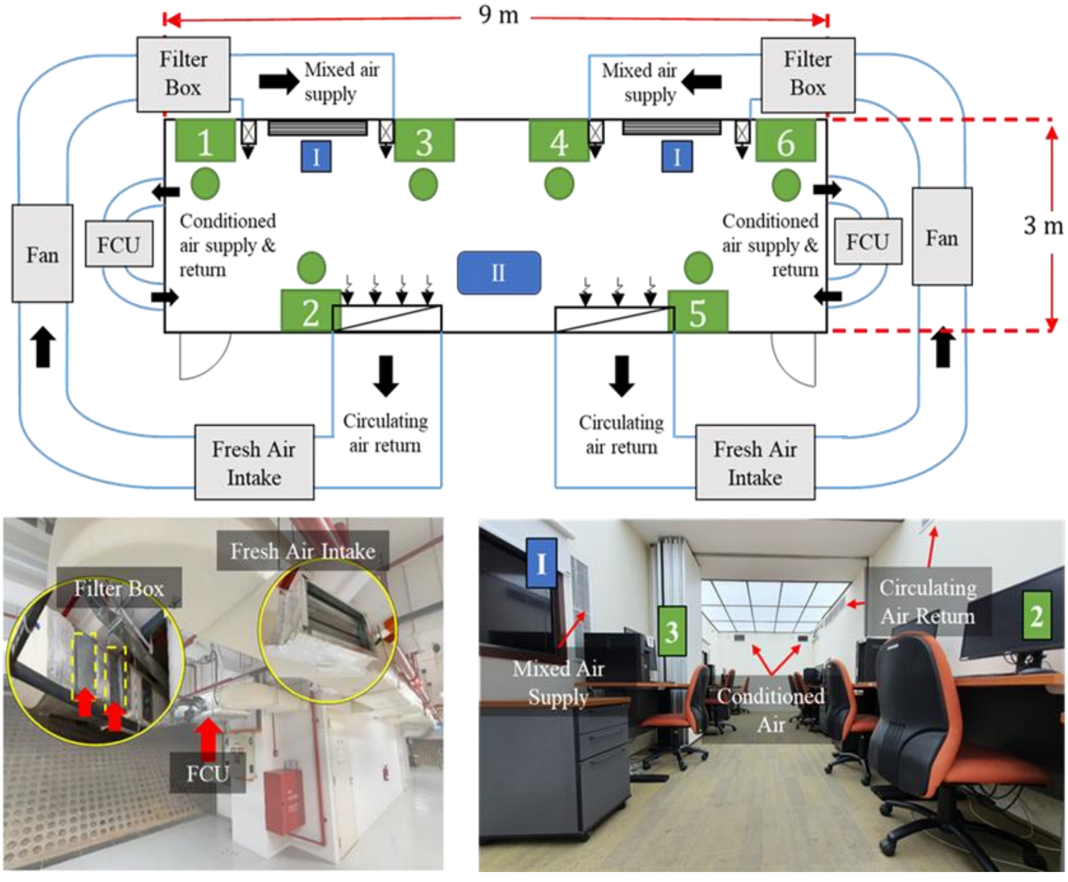


Figure 3-1. Schematics of the environmental chamber. The illusion of windows is indicated as (I). The IAQ parameters were measured on an IAQ station at a raised height of 1.5 m from the ground and 1 m away from participants was placed in the middle of the room labelled as (II). The work desks were numbered for easy identification of participants. The fan runs at 300 L/s, and FCU (fan coil unit) operates at 150 l/s. The filter box was designed with hidden slots dedicated to carbon and PM filters with adjustable fresh air intake allowing for variation in the ventilation rate.

During the study, the air temperature in the environmental chamber was maintained at 24℃ - 25℃ with a relative humidity of 50% - 60%. The light intensity at the desktop level was maintained at 500 lux in line with SS 531 (Singapore Standard Council, 2013), 300-500 lux, and the noise level was maintained at 54.8 dBA (8-hour average) in line with OSHA (2016), 90 dBA, 8-hour day exposure. The floor carpet was vacuum cleaned a week before the start of each round.

3.2.2 Study Conditions

The study conditions were achieved through mechanical intervention using air filters to administer six conditions over 7 weeks per round. The testing sequence begins with Week 0, which was used to train the participants. The condition set for week 0 was at 1 ACH with no filters in the filter boxes. The air circulation system was set at a ventilation rate of 1 air change per hour (ACH) or 18 L/s, denoted as 'HV'. This ventilation rate fulfils the minimum fresh air supply rate of 0.6 L/s-m^2 for offices recommended in SS 553 (Singapore Standard Council, 2009). For the subsequent six weeks, the conditions were varied by lowering the ventilation rate to 0.5 ACH (denoted as '**LV**'), inserting a PM filter (denoted as '**PM**'), inserting a carbon filter (denoted as '**C**') or inserting both filters (denoted as '**PM-C'**) refer to Figure 3-2.

Study Conditions			
Ventilation rate	$PM_{2.5}$ (Particulate filter)	TVOC (Carbon filter)	$PM_{2.5}$ + TVOC (Combined)
1.0 ACH	HV-PM	HV-C	HV-PM-C
	HV	HV	HV
0.5 ACH	LV	LV	LV
	LV*	LV*	LV*

LV: Low ventilation **HV**: High ventilation **HV-C**: High ventilation with Carbon **HV-PM**: High ventilation with particulate matter filter **HV-PM-C**: High ventilation with particulate matter filter and carbon

Figure 3-2. Experimental study conditions. Each colour indicates one study condition. The experiment hypothesis investigates the difference between the study conditions as indicated by the red delta.

The PM filter used is a combination of a G4 (CAMFIL 30/30 Panel Filters) and an F8 (CAMFIL EcoPleat G 3GPPS-12244-F8) particulate filter, which has a rating of ePM1 at 70% (European Standards, 2019). The carbon filter used is a CAMFIL Gigapleat

NXPC C3 (ASHRAE, 2016; International Standards, 2014) for TVOC reduction. The ventilation rate for both HV and LV conditions was measured by the tracer gas decay method using CO_2 as the tracer gas. The LV condition was repeated twice in each round. Any learning effect (participant increased proficiency in the task over time) could be detected and be offset from the effects of changing the IAQ conditions in subsequent data analysis. The study condition changeover was done the day before the start of the study week except for round 3. Due to the overwhelming response, the study conditions were changed on the last day of the testing week. The ventilation rate was increased to its total capacity to stabilise the study condition overnight.

The ventilation rate for all the study conditions was estimated using the tracer gas (CO_2) decay technique. The technique was administered a month before the start of the study (for each round) according to the European Standards (2017). During the test, the room and the immediate vicinity had no occupants. At the start of each test, both the inlets and outlets of the ventilation system were closed and sealed. Using a high-pressure gas cylinder, CO_2 was injected into the chamber. The inlets and outlet vents were opened when the CO_2 concentration reached approximately 4000 ppm using a CO_2 data logger. The ACMV system was switched on and maintained at a constant rate. The test ended when the CO_2 concentration dropped to approximately 600 ppm (equivalent to the average outdoor CO_2 concentration).

The mass balance equation of the tracer gas can be written as Equation (3-1):

$$V.\frac{dC(t)}{dt} = G + Q.C_{out} - QC(t) \tag{3-1}$$

Where,

V (m^3) = volume of the chamber,

C(t) (ppm) = concentration of the tracer gas at any given instant t,

t (s) = time,

G (m3/s) = generation rate of the tracer gas,

Q (m^3/s) = internal and external exchange rate and

C_{out} (ppm) = external concentration of CO_2.

Solving Equation (3-1) leaves the analytical solution to Equation (3-2):

$$C(t) = C_{out} + \frac{G}{Q} + \left(C_{in} - C_{out} - \frac{G}{Q}\right).e^{-\frac{Q}{V}t} \quad (3\text{-}2)$$

Where,

C_{in} = initial concentration at the beginning of the decay period.

The absence of an external CO_2 source assumed no generation of the tracer gas. Hence the, Equation (3-2) can be simplified as Equation (3-3):

$$\frac{Q}{V} = \frac{\ln\left(\frac{C_{in} - C_{out}}{C(t) - C_{out}}\right)}{t} = \mathrm{N} \quad (3\text{-}3)$$

Where,

N (h^{-1}) = air change rate per hour (ACH),

The ACH is estimated by the slope of the line that represents $\ln\left(\frac{C_{in}-C_{out}}{C(t)-C_{out}}\right)$. The normalised concentration against time. According to the study condition requirement, the fresh air supply vent angle was adjusted according to the vent's face velocity.

3.3 Study Protocol

3.3.1 Environmental Monitoring

The air monitoring station placed in the middle of the chamber was 1.5 m above the ground (in line with the participant’s breathing zone) and 1 m away from the participants, according to SS 554 (Singapore Standard Council, 2016). All office chairs in the chamber were adjusted to the same height to account for the height differences and ensure that participants were in the same breathing zone. The moderator ensures that participants do not get close to the air monitoring station (potential data influence from bio-effluents such as TVOC) and refrain from adjusting the chair's height (but were allowed to adjust the monitor to suit their comfort level) during the study. The IAQ station was noise proofed with thick sponges to cancel out the motor noise from the equipment, as shown in Figure 3-3. This was to ensure that participants were not affected by the background noise (distraction or lack of concentration), and if they did so, disposable ear plugs were provided.

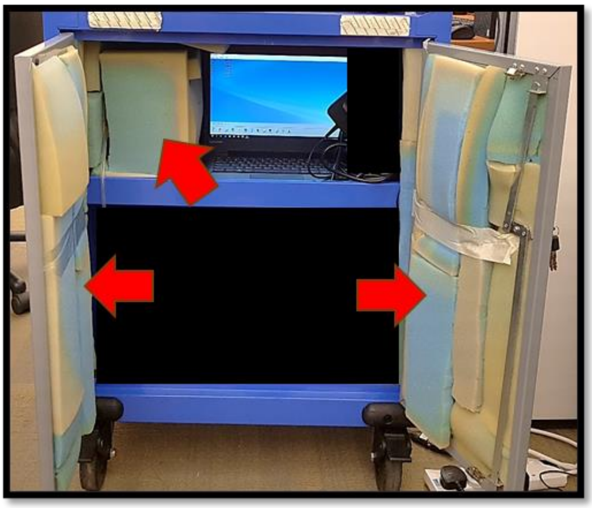


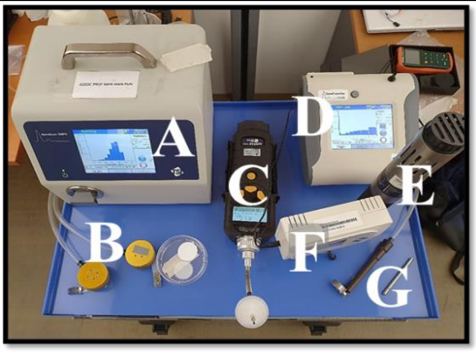
Figure 3-3. The IAQ station, inside the station where the sampling pumps were kept and locked. The doors were cushioned with thick sponges to absorb the noise from the equipment. The noisy sampling pump had an additional cushioning layer to create an enclosed environment to reduce noise.

Equipment used to monitor the IAQ parameters follows the WHO (2010) and SS 554 (Singapore Standard Council, 2016) definitions. Thus, the equipment used in this study was designed for IAQ monitoring (sensitive to low concentration). Therefore, the equipment placed on the cart was carefully studied before adopting the arrangement shown in Table 0-1. For instance, the Nanoscan SMPS Nanoparticle Sizer 3910 operates using a wick soaked in 90% isopropyl alcohol. Therefore, placing equipment designed to sample VOCs next to Nanoscan SMPS Nanoparticle Sizer 3910 influences the TVOC data. Among the listed active sampling equipment that required lab or external analysis were:

- SKC single-stage Personal Modular Impactors designed for PM_1 and $PM_{2.5}$ gravimetric analysis (Table 0-1, (B)).
- Tenax® TA Sorbent Tubes with porous polymer as the sorbent for VOCs and GCMS (Agilent 7890B/5977A) was used to analyse the data using EPA method TO-17 (Table 0-1, (G)).
- BioStage single-stage cascade impactor designed for viable micro-organisms sampling such as bacteria and fungi and SKC Flite 3 Pump at 14.2 L/min flow rate for colony culture analysis.

The sampling equipment was integrated with an 8-hour active air sampling SKC Leland Legacy Pump (PM_1 – 8.6 L/min and $PM_{2.5}$ – 10 L/min) and SKC Pocket Pump TOUCH (VOCs – 68 ml/min) flow rates. The analysis involves thermal desorption of the collected samples. The resulting chromatogram involves cross-referencing with the NIST library from MassHunter Qualitative Analysis software with a match score of 90.0 %-99.0 % of similarity. The concentration for TVOC was obtained using a single point external standard method on compounds with a match score of >80% (refer to Appendix A for details). The TVOC concentration obtained does not underestimate the concentration levels present in the chamber. The match score identifies the chemical compound by comparing the retention time and the area with the library to identify the compounds. The VOCs, PM_1 and $PM_{2.5}$ samples had one blank and one passive VOC duplicate for each analysis. The samples were blank corrected during the lab analysis. Due to inaccuracy in weighing balance, the data obtained from the Personal Modular Impactors were not used in the analysis. Since the duplicates for VOCs were passive, the retention area in the graph was not as significant as the samples but the spikes overlapped with the sample's data. The data used for further analysis are reported in Section 3.6.

Table 3-1. List of active sampling equipment. The alphabetical reference on the image is in line with the alphabetical reference in the table. The table also highlights the operating range of the associated indoor air pollutant and the equipment used.



Equipment		Operating Range	Indoor Air Pollutants	Sampling Frequency
A	NanoScan SMPS Nanoparticle Sizer-TSI 3910	10 - 420 nm Accuracy: ±10% at 0.25 lpm	$PM_{2.5}$	1 min
D	Optical Particle Sizer	0.3 - 10 μm Accuracy: ±5% at 0.5 μm		1 min

	(OPS)-TSI 3330				
C	ppbRAE 3000	1 ppb – 10000 ppm Accuracy: 10 – 2000 ppm: ±3% at calibration point		TVOC	1 min
E	Graywolf IQ-610	CO_2	0 – 10,000 ppm Accuracy: ±3%rdg ±50 ppm	CO_2, CO, O_3, Temperature and Relative Humidity	1 min
		CO	0 – 500 ppm Accuracy: ±2 ppm<50 ppm, ±3%rdg >50 ppm		
		O_3	0 – 1 ppm Limit of detection: 0.02 ppm		
		Temperature	10℃ – 70℃ Accuracy: ±0.3℃		
		Relative Humidity	0 – 100 %rh Accuracy:±2 %rh <80%rh (±3%rh >80 %rh)		
F	Shinyei Multi mode Monitor-FMM-MD	10 – 1000 ppb Accuracy: ±4 ppb <40 ppb, ±10% of reading ≥40 ppb		Formaldehyde	30 min

The ambient air quality monitoring was done using the national environment agency Singapore (NEA) website (National Environment Agency, 2018) and its app (AQICN, 2018) directed at the location where the study was done. The air quality reports were updated hourly with the sub-index of the concentration of the pollutants to establish any potential influence of outdoor contaminants on the indoor environment. The air quality pollutants reported on the NEA website available to the public were $PM_{2.5}$, PM_{10}, Sulphur dioxide, Ozone, Carbon monoxide, and Nitrogen dioxide. However, the list does not contain CO_2 concentrations. Therefore, Testo 480 (range: 0 – 10000 ppm) was used to monitor the ambient CO_2 concentration. The equipment was located close to the fresh air supply vent. There was no report for the concentration of Nitrogen dioxide on the NEA website. Therefore, due to the sources identified surrounding the chamber, the research team decided to test the ambient concentration of the immediate vicinity outside the chamber for Sulphur dioxide, Nitrogen dioxide, and Radon with Singapore Test Services Pte Ltd. the outcome is presented in Table 0-2.

Table 3-2. Exposure assessment by Singapore Test Services Pte Ltd. compared to Singapore Standard SS 554 and reference to WHO.

Pollutant	Sampling method	Duration	Average concentration	SS 554[1]	WHO[2]
Sulphur dioxide	Filter membrane	8 hours	0.002 mg/m^3	-	0.02 mg/m^3 (24 hrs)
Nitrogen dioxide	Sorbent Tube	8 hours	< 0.04 mg/m^3	0.04 mg/m^3	-
Radon	Radon Kit	90 hours	40.7 Bq/m^3	100 Bq/m^3	-

Note:[1](Singapore Standard Council, 2016) and [2](WHO, 2010)

Since all reported pollutants from Table 0-2 were found to be at relatively low concentrations to have any effect on the study, these pollutants were not sampled for the entire duration of the study.

3.4 Participant Protocol

3.4.1 Determining the Sample Size

The sample size is determined based on Cochran's sample size Equation (3-4) for an unknown population with an unbiased sample (Bartlett et al., 2001). Using equation (3-4), the maximum allowable sample size for categorical data is 384 with a margin of error of ±5% at a confidence interval (CI) of 95%, and the minimum allowable sample size is 68 with a margin of error of ±10% at confidence interval (CI) of 90%. Anything lower than the minimum allowable sample size would yield inaccurate results.

$$N = z^2[SD]\frac{(1 - SD)}{E^2} \tag{3-4}$$

Where,

N = required sample size,

Z = Z - score of 1.645 (CI of 90%) or 1.960 (CI of 95%),

SD = standard of deviation of 0.5,

E = the margin of error of $\pm$10% (CI of 90%) or $\pm$5% (CI of 95%).

Moreover, Bartlett et al. (2001) reported that when multiple regression analysis examines the study outcomes, it is important to avoid overfitting. Therefore, Halinski & Feldt (1970) and D. E. Miller & Kunce (1973) reported a conservative ratio of 10:1 (observations to independent variables) as optimal for multiple regression analysis. The study measures nine independent variables ($PM_{2.5}$, TVOC, Formaldehyde, Carbon Monoxide, CO_2, Ozone, Bacteria Count, Fungi Count, and Weeks) based on the correlation test (see section 3.5.1). Hence, using the conservative ratio of 10:1, the sample size is 90. However, the conservative ratio is limited by the number of independent variables defined in the study. For instance, if gender was included as one of the independent variables, the sample size required will increase to 100 participants. In addition, studies have shown that females have better cognitive performance than males in perceptual speed, accuracy and motor skills, whereas males showed better performance in working memory and mathematical skills (Halpern, 2000, 2016; Mann et al., 1990). Therefore, to balance these differences, an equal number of female and male participants were studied, with the differences among participants accounted for in the statistical model (see section 3.5.3).

For an unbiased sample size and considering the physical limitation of the environmental chamber and the constraints of the study, the research team aimed to achieve a minimum of 90% of confidence interval (68 participants) and a maximum of 90 participants with an equal number of female and male participants. Therefore, to achieve a maximum of 90 participants, the study was administered over three rounds while no changes were made to the experimental design.

3.4.2 Participant Recruitment

Figure 3-4. The recruitment poster reached out to potential participants through the university's mass email system.

The study population was recruited using the university's mass email system to reach out to students from all levels and disciplines by advertising through the poster shown in Figure 0-4. For rounds 1, 2, and 3, we received an overwhelming initial interest of 119, 411, and 639, respectively, which amounts to 1169 interest. Unfortunately, due to the limited capacity of the chamber, only 42 participants per round were possible.

Since the study's hypothesis was to find the association between IAQ and cognitive performance, it was essential to ensure that the effects observed were due to the exposure to the study conditions and not due to the underlying conditions of the individuals. Therefore, the research team restricted the population to non-sensitive and healthy individuals. The research team took Allen et al. (2016) screening criteria as the baseline and included suitable criteria for the study population. The population was then screened for current or social smokers, chronic diseases (such as asthma), learning disorders, colour-blind, allergies (because of testing of indoor air quality), psychoactive medication, and claustrophobia (because the participants were required to remain in the room most of the study) through a google document survey. They had to complete the survey when expressing interest in participating. Those who indicated positive were excluded from the study.

3.4.3 Participant Demographics

After the screening, randomly selected participants were notified through email to seek their final confirmation of the dates. Of the 92 (Round 1: 20; Round 2: 31; Round 3: 41) participants recruited, 90 completed the study with one moderator to provide standardised instructions and answer any questions from the participants. The study was concluded with 2 participants dropping out. The recruited study population was diversified students (21-35 years of age) at the Nanyang Technological university of Singapore. The demographics of the 90 participants are shown in Figure 0-5.

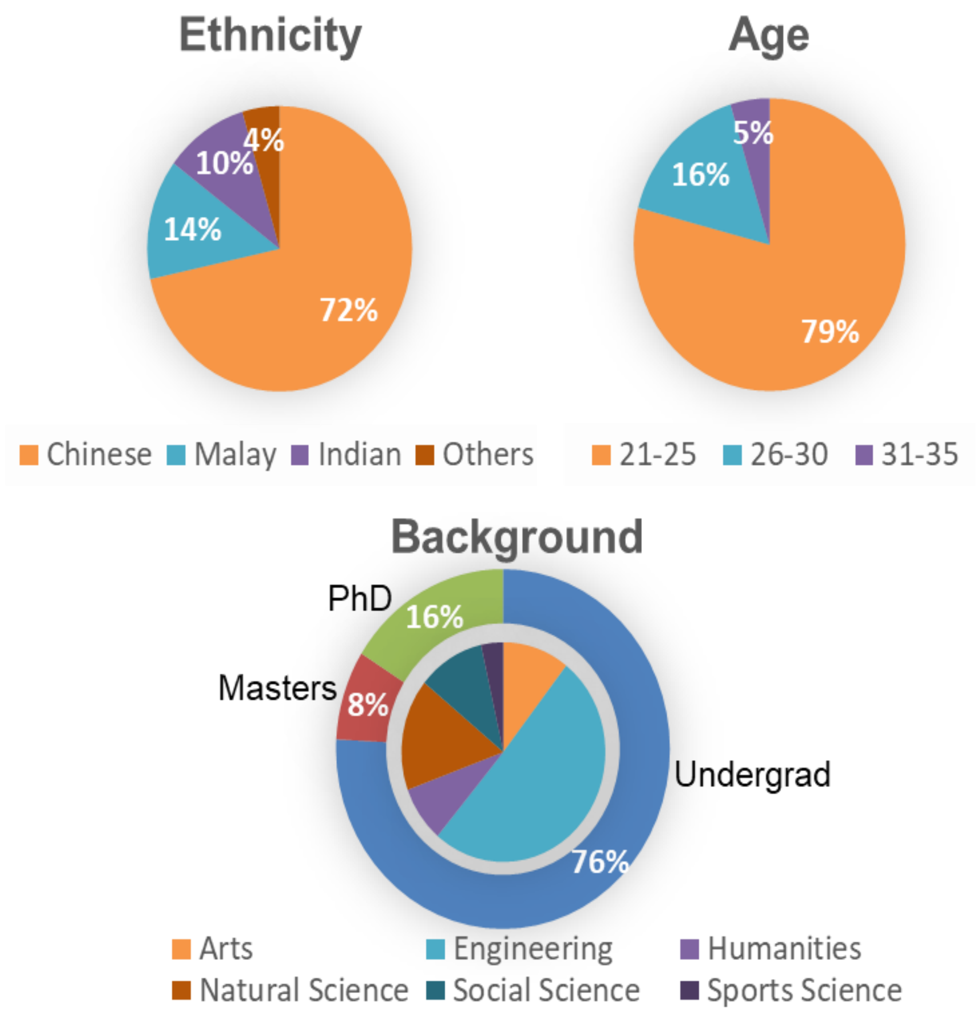


Figure 3-5. Demographics of participants who completed the study.

3.4.4 Participant's Study Schedule

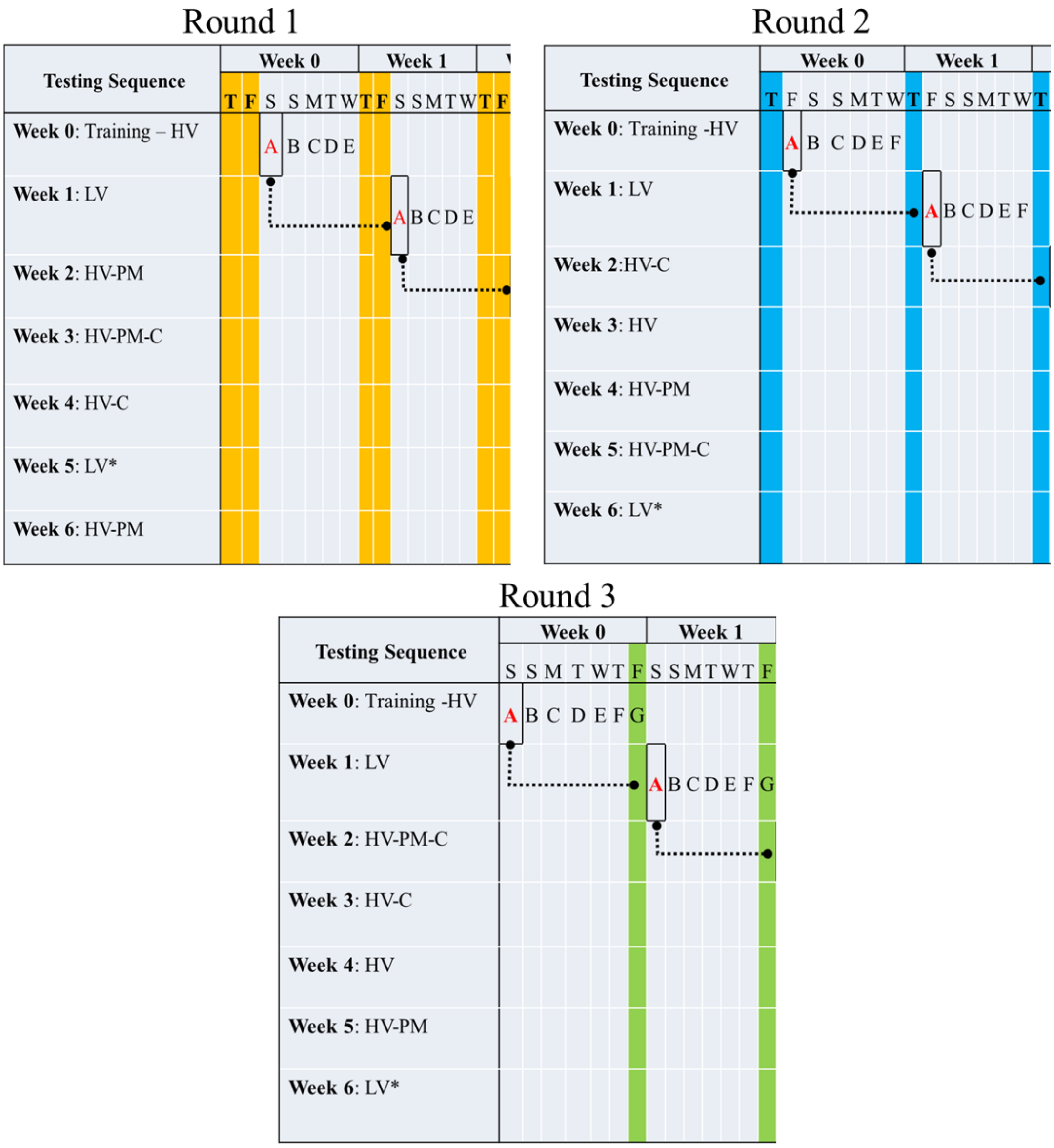


Figure 3-6. The participants' reporting schedules for all rounds. Participants were divided into subgroups indicated as alphabets (A-G) spreading over different days of the week. The highlighted day(s) in yellow, blue, and green were reserved to change the study conditions and stabilise the concentration levels. For round 3, it was done after the participants completed the study. Testing sequence: HV- indicates high ventilation (1 ACH), LV – indicates low ventilation (0.5 ACH), PM – indicates PM filter inserted, and C – indicates carbon filter inserted. *Repeated condition.

The participants were divided into three rounds (Figure 3-6) following the same protocol. For each round, participants attended a training session (Week 0) of the first week to get familiarised with the daily protocol and dampen any potential learning effect (Newell & Rosenbloom, 1981). Participants in each round were rotated weekly and reported back to the chamber on the same day of each week, i.e., Monday participants reported to the chamber each Monday of the 7 weeks. Participants were not allowed to switch desks between weeks; hence the desk they chose on week 0 was assigned to them for the rest of the 6 weeks. So that during the data analysis, participants could be associated with the task. During recruitment, participants were asked to indicate which day of the week would they commit for the whole day (8 hours) and be able to commit for that same day on 7 consecutive weeks. Thus, they might have a week affected in a rare situation such as during a university examination. In such a situation, we try to accommodate by reshuffling within the same week. The reshuffling and desk re-allocation was accounted for by assigning each participant a participant identification digit (PID), which is neutral to their identification and was used as a random variable in the statistical analysis reported in Chapters 4 and 5 and 6. The results from Week 0 were not included in the analysis.

3.4.5 Daily Protocol

The 8-hour study was broken down into morning sessions and afternoon sessions. Similarly, in the study conducted by Allen et al. (2016), participants were tested for their cognitive abilities at the end of the day and were allowed to do their work for the first half of the day. However, given the demographics of the study population, allowing participants to do their work would create irregular biases. For instance, one could choose to sleep during the day, and the other might be rushing through to finish up assignments leading to irregular cognitive load as they go through the day. Therefore, it became essential for the proposed protocol to engage the participants and pose a challenge to them. There were three potential problems highlighted; participants were growing bored (6 weeks of the same task), heavy usage of social media (distraction, loss of concentration on task), and self-declared long breaks (exposure to conditions not designed for the study). Therefore, a pilot study was done to address these problems and to determine a suitable protocol comprising a series of cognitive tests and activities.

3.4.5.1 Highlights of the Pilot Study

A pilot study was done to test the feasibility of the daily protocol (morning and afternoon sessions) to be included in the final protocol for the single-blind chamber study. The study was done in a tutorial room (maximum occupancy of 20) located in the Nanyang Technological University, Singapore, for three consecutive days with five randomly chosen university students with a mean age of 25 years. Out of the five participants, 3 were Chinese undergraduates, 1 Malay postgraduate, and 1 Malawian postgraduate. Participants were screened for medical history such as colour blind and cognitive disabilities before volunteering for the study. For the electroencephalogram (EEG) test, 2 out of 5 participants volunteered to participate. Participants were told to bring their laptops to administer the activities. Before the commencement of the study, participants had to sign informed documents about the study and were compensated with SGD 150 upon completion.

3.4.5.1.1 Study Design

The study lasted for 3 consecutive days, lasting for 8 hours (0900 - 1700). The morning session ends at lunch break, and the afternoon session begins after the lunch break. The variation of activities is summarised in Figure 3-7. All 3 days began with briefing the participants on the overview of their assigned activities in those 8 hours. Participants were to refrain from using their phones when engaged in the activities. Participants were instructed only for emergency purposes to get in touch with the moderator as the first point of contact during the study. At the end of each day, verbal feedback about the day’s protocol was collected from each participant. The following day’s protocol was adjusted according to the feedback received.

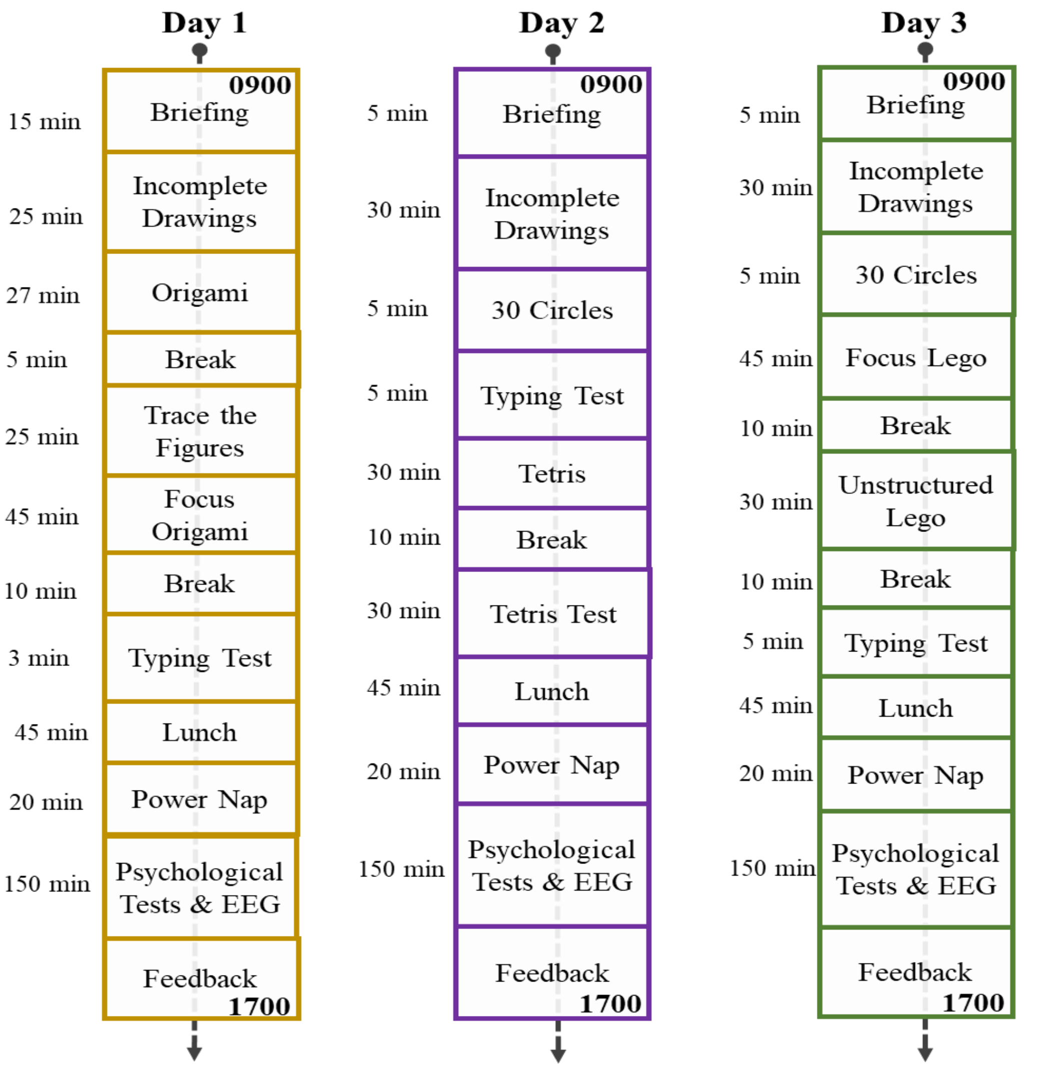


Figure 3-7. Summary of activities tested during the pilot study. The testing includes optimising the duration for each task upon participants' feedback.

The study was designed to expose participants for 8 hours under the same study condition before testing for their cognitive performance. This is to ensure ample time for the participants to settle down and get used to the environment. Hence, participants were assigned light tasks and hands-on activities in the morning. It is critical to note that the study's design ensures that all participants had the same amount of exposure, breaks, and light tasks.

3.4.5.1.2 Morning Session

The morning session comprises different activities targeted to test motor skills or creativity. The objective of the morning session was to investigate the process of the activity and if it could engage the participants and create a distinction between the morning and afternoon sessions. Thus, the selected activities had to be fun, light (nothing too draining) and hands-on for the participants. According to the flow theory, easy to solve activities, despite being perceived as fun, will induce boredom in the long run (Csikszentmihalyi, 1997). Hence, activities like incomplete drawings, origami, Lego, alternative uses test (AUT), typing test, and mirror tracing were chosen to test its process feasibility. Incomplete drawings, Origami, and Lego were tested once, mainly due to the feedback from the participants. Whereas alternative uses test (AUT), typing test, and mirror tracing were tested over 3 days. Details of each task tested for feasibility can be found in Appendix B.

The feasibility of an activity can be expressed in four factors: duration, quantification, level of difficulty, and engagement. The duration of an activity is the least important factor as it could be easily modified and implemented. Quantification indicates whether the existing quantification method requires modification to tailor to the activity. Csikszentmihalyi's flow theory (the experience of enjoyment when people's attention is fully absorbed by doing an intense activity even at risk) defines the factors: difficulty and engagement, affecting the participant's flow experience (Csikszentmihalyi, 1997). Therefore, the activities tested need to fulfil a minimum of 2 factors to be considered in the final protocol.

Table 3-3. Summary of morning activities that meets the feasibility test criteria. Bold activities were selected for the finalised protocol. The 'X' indicates fulfilling the feasibility conditions.

Morning Activity	Duration	Quantification	Difficulty	Engagement
AUT	X	X	Medium	X
Typing Test	X	X	Easy	X
Mirror Tracing		X	Medium	X
Incomplete Drawings	X		Too Easy	
Origami			Too Difficult	
Tetris			Easy	X
Lego	X		Difficult	X

The feasibility of the 7 activities tested and the four factors (duration, quantification, difficulty, and engagement) are summarised in Table 3-3. A cross ('X') indicates the fulfilment of activity has met the required feasibility condition. Only 2 out of 7 activities (incomplete drawings and origami) were unsatisfactory. This is because the activities had failed to engage the participants by coming across as either too easy or too complicated, and there was no cost-effective verified procedure to quantify the output. The other 5 activities (highlighted in bold in Table 3-3) met the feasibility requirement. Among these selected 5 activities (AUT, typing test, mirror tracing, Tetris, and Lego), those were categorised as easy (typing test and Tetris) and were included in the final protocol as a time-filler. This is because of the flow experience. Engaging in the same activity for a longer time introduces boredom to participants, which will affect the data as they might not be fully engaged for some weeks. Therefore, the AUT and mirror tracing were categorised as easy and medium, as shown in Table 3-3. Since it fulfilled the feasibility criteria, it was included in the final protocol as time-filler activity.

Thus, an activity should be challenging and engaging to benefit from the flow experience. Lego falls into that category. Therefore, Lego activity was included in the final protocol for the single-blind chamber study. The disadvantage of the activity was that there was no existing quantification method. An adaptation of a verified method is discussed in Chapter 4.

3.4.5.1.3 Afternoon Session

The afternoon session comprises lunch, a power nap, and a set of PEBL test battery which includes electroencephalogram (EEG) recording. The objective of the afternoon session was to investigate the perceived difficulty, the ease of understanding the task requirements, and the comfort level of using EEG and the PEBL test battery (refer to Appendix A). The feedback from the participants was to choose a challenging version of the PEBL test battery. There was no distraction or discomfort from the EEG device and recording procedures. The choice of food for lunch and the implementation of 20 minutes of power nap was encouraged.

3.4.5.1.4 Summary

In summary, the pilot study done with 5 participants assisted in identifying the feasibility of the activities done in the morning session protocol and refined the afternoon session protocol through participants' feedback. The morning session protocol consists of Lego to test creativity, whereas AUT, typing test, mirror tracing, and Tetris were categorised as time-filler activities. The afternoon session protocol consists of lunch, 20 minutes of power nap, and a psychological test battery broke into two parts: with EEG testing and without EEG testing.

3.4.5.2 Finalised Protocol

The same protocol was administered each day of the study for 7 weeks, summarised in Figure 3-8. The timeline indicates the different segments of the protocol that was implemented. This section elaborates on the protocol segments presented in Figure 3-8.

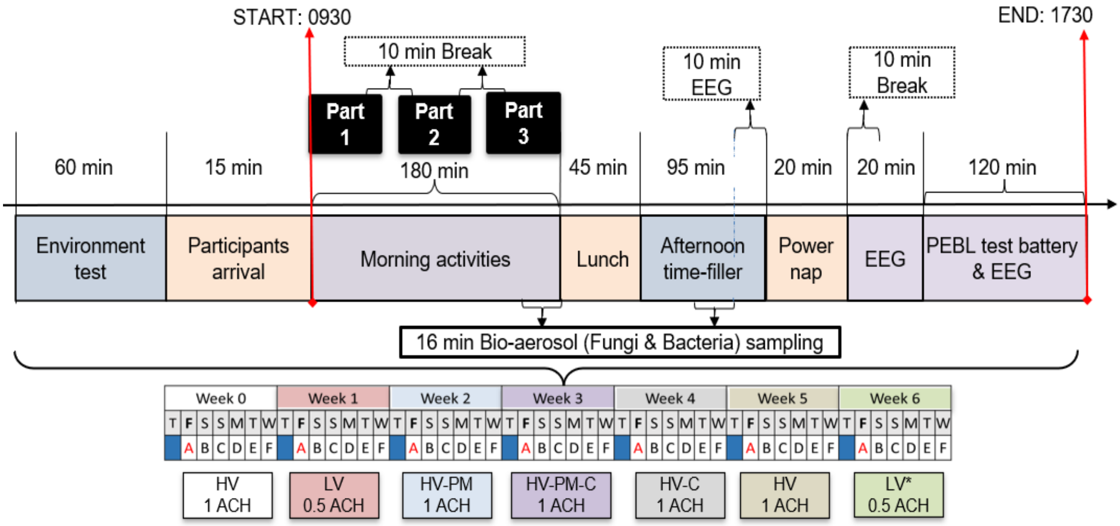


Figure 3-8. Timeline of the finalised participant protocol. The different group of participants is denoted as ‘A’, ‘B’, ‘C’, ‘D’, ‘E’, and ‘F’, respectively, indicating the weekly rotation on the same day with randomised experimental conditions for each round.

The protocol began with an environment test before the arrival of the participants. This was to ensure the change of IAQ (safety of the participants) and the set points (the temperature at 24°C - 25°C, relative humidity at 50% - 60%, and light intensity at 500 lux) were at the defined levels. The set points were in line with Singapore standards (Singapore Standard Council, 2013, 2016). The safety of the participants was monitored using the Carbon Dioxide monitor (Testo 480). The instantaneous measurements were kept below the Singapore standards, SS 554 (700 ppm above the outdoor level, typically around 400 ppm) (Singapore Standard Council, 2016).

The morning activities segment was divided into three parts: time-fillers randomly selected from Y8, a free platform for a vast variety (approximately 3443 single player

Y8 games) of browser games (Y8, 2021) and hands-on activities, as stated in section 3.4.5.1.2. The details of each part, sequence, and duration are listed in Table 3-4.

Table 3-4. List of time-filler and activities administered in micro activities, a segment of the daily protocol.

Week	Part 1	Time	Part 2	Time	Part 3	Time
0	Unblock me	20 min	Typing test	10 min	SBP	40 min
	Battleships 2	20 min	AUT	10 min	Tetris	15 min
	Focused Lego	20 min	Mirror tracing	5 min	Axon	5 min
1	Unblock me	20 min	Typing test		SBP	
	Bloxroz	20 min	AUT		2048 battle	
	Focused Lego	20 min	Mirror tracing		Boat drive	
2	Unblock me	20 min	Typing test		SBP	
	Sudoku	20 min	AUT		2048 Merge	
	Focused Lego	20 min	Mirror tracing		Coloruid 2	
3	Unblock me	20 min	Typing test		SBP	
	Supreme checkers	20 min	AUT		Triangular 2048	
	Focused Lego	20 min	Mirror tracing		Snake and blocks	
4	Unblock me	20 min	Typing test		SBP	
	Chess	20 min	AUT		Toetrix	
	Focused Lego	20 min	Mirror tracing		Tube racer	
5	Unblock me	20 min	Typing test		SBP	
	Jigsaw sudoku 2	20 min	AUT		Tetrisnake	
	Focused Lego	20 min	Mirror tracing		Sparks recharged	
6	Unblock me	20 min	Typing test		SBP	
	Bloxroz	20 min	AUT		2048 battle	
	Focused Lego	20 min	Mirror tracing		Boat drive	

Parts 1 and 3 comprised two time-filler computer browser games, ‘Focused Lego’ and serious brick play (SBP). Focused Lego was administrated in part 1 to familiarise participants with the provided set of bricks by building different models with step-by-step guidance. It was not administered at the end of part 2 due to the possibility of replicating the models for SBP (part 3) and creating boredom with similar activities. Part 2 comprises time-filler activities highlighted in section 3.4.5.1.2. Participants were provided with a summary list that provides instructions on 'how to play' rules for all activities as a reference and overview of the testing day.

Previous studies have shown that food intake affects cognitive functions in a short period (DW Documentary, 2021). Participants were reminded through text messages the evening before the test day to avoid alcohol consumption, refrain from food and drinks high in sugar, and have 8-hours of sleep. The rationale was explained to the participants as these factors could affect the study results and abstain from alcohol before the test day. However, we did not track and record participants' consumption and sleep quality before the testing day due to a lack of resources. Before and during the study, participants were told to avoid high sugar or caffeine-rich eiblables (Satish et al., 2013) except for habitual caffeine, representing normal behaviour (Haskell et al., 2005). Hence, allowing variation for lunch for an 8-hour study would highly compromise the study's robustness. Therefore, lunch is deemed as a control for the afternoon activities. Therefore, a standardised lunch was provided with dietary variation with approximately the same calories.

Participants were given 45 minutes of lunch with a mineral water bottle and a 6-inch Subway sandwich (Buffalo Chicken for non-vegetarians and Chatpata Chickpea for vegetarians) according to their dietary requirements. An approximate 400 calories were maintained regardless of the dietary requirement. Mineral water bottles were provided to each participant once they entered the chamber (where the study was carried out). If they required more water, they were told to ask the moderator. Participants were to refrain from taking any other food or sweet drinks. No food was allowed into the chamber apart from water for hydration.

After lunch, to get the participants settled in, the afternoon protocol started with 3 time-filler browser games; airport madness (25 min), plumber (25 min), and vex (35 min). Over the 7 weeks, these games were changed in versions (i.e., vex played in week 1 and vex 2 in week 2). A slight change between the versions means an additional level or obstacle to cross, yet the game's main objective remained the same throughout the versions. Finally, the last 10 minutes were allocated for EEG calibration. Participants were required to fix the saline covered electrodes into the device and calibrate the device on their heads before taking a 20-minute power nap. This procedure gets participants comfortable with the device and the calibrating procedures while resting to minimise the effects of fatigue. Furthermore, this gave fewer errors in connection failures and the need to troubleshoot on the specific electrodes. Hence, the recalibration was less time consuming due to the increase in comfort levels in handling the device. Hence, this procedure was essential to achieve 100% connectivity in all electrodes and increase comfort among participants with less or no frustrations (i.e., distraction affects concentration, and rushing through by guessing the answers due to discomfort).

The morning protocol kept the participants engaged with a minimum number of allocated breaks. As a result, fatigue from the morning could build up in the afternoon, which was a concern. To mitigate this problem, we looked at several cultures in China, Italy, Spain, and Japan. They all had a common aspect of having a mid-afternoon workday break to reduce fatigue. National Sleep Foundation did a survey that reported that 34% of USA companies that allowed naps during breaks at work had seen a decrease in fatigue and increase in concentration. The promising statistics and the specific duration reported in previous studies introduced a power nap in the mid-afternoon for 20 minutes (Hayashi et al., 1999; Milner & Cote, 2009; WHO, 2010). Participants were strongly encouraged to use the 20 minutes to rest, and they were not allowed to use their phones or step out unless in an emergency. The lights in the chamber were dimmed off to create the environment for a power nap.

The last segment comprises a PEBL test battery (Chapter 5) done in one sitting in 90 minutes and recording EEG responses (Chapter 6). Once completed, participants were allowed to leave the chamber, marking the end of the daily protocol.

Throughout the daily protocol, a series of 10 minutes breaks were allocated to participants for toilet breaks and or water breaks. Participants who did not wish to have a toilet break remained in the chamber. The breaks were designed to be below 15 minutes so that any short-term exposure does not affect the participants according to occupational exposure limits (CCOHS, 2021).

A moderator was present throughout the daily protocol to ensure that all segments were implemented as designed with no variations between the days and weeks of the study apart from week 0 (training week). The training week required more guidance from the moderator for explaining the schedule, the rules of each activity, and ensuring participants understood each of the activity's instructions, which aided in removing external factors such as confusion and misunderstanding of the instructions for weeks 1 - 6. This ensured the creditability of the data collected from this study. From weeks 1 - 6, the moderator continuously observed any participants guessing answers (PEBL test battery & EEG segment). Participants were told by the moderator at the beginning of the study to avoid guessing the answers. If found to do so, they were asked to do the activity again. The guessed data is omitted in the data analysis. Participants were not allowed to leave the chamber in the middle of an activity.

3.5 Statistical Analysis

The statistical model and analysis adopted for Chapters 4, 5, and 6 are described in detail in the following sections. Since the study was done in Singapore, the IAQ reference limit adhered to in this study is based on benchmarking Singapore Standards as the upper limits.

3.5.1 Determining the Covariates

Measuring the complex chemical mechanism of IAQ cannot be based on a single parameter. Therefore, various parameters listed in SS 554 were measured, and the interaction among these parameters was assessed for weak associations. The weakly associated parameters are categorised as independent variables in the statistical model.

Pearson's product-moment correlation test was used to identify the weak association of IAQ parameters (Ozone, Temperature, Relative Humidity, Carbon Dioxide, Carbon Monoxide, Formaldehyde, Fungi count, and Bacteria count) with the experimental IAQ parameters ($PM_{2.5}$, TVOC, and CO_2). The concentration of Ozone was excluded from the analysis since the concentration levels throughout the study showed an average of 0 ppm. Temperature (23-25 °C) and relative humidity (<65 %) were tightly regulated in the study so that cognitive performance was not compromised (Lan et al., 2022). Therefore, it was not included in the correlation test. The weakly associated parameters (both positive and negative) were then classified as covariates (independent variables). According to Akoglu (2018), parameters that exhibit weak or very weak associations (both positive and negative) with a correlation coefficient of r, less than 0.4, were included as covariates. This means that more than 16% of the variation is associated with the variation of the other corresponding parameter. In Figure 3-9, the correlation matrix shows all correlation coefficients as weakly associated with the experimental parameters. Therefore, the covariates used in the analysis were formaldehyde, carbon monoxide, bacteria count level, and fungi count level.

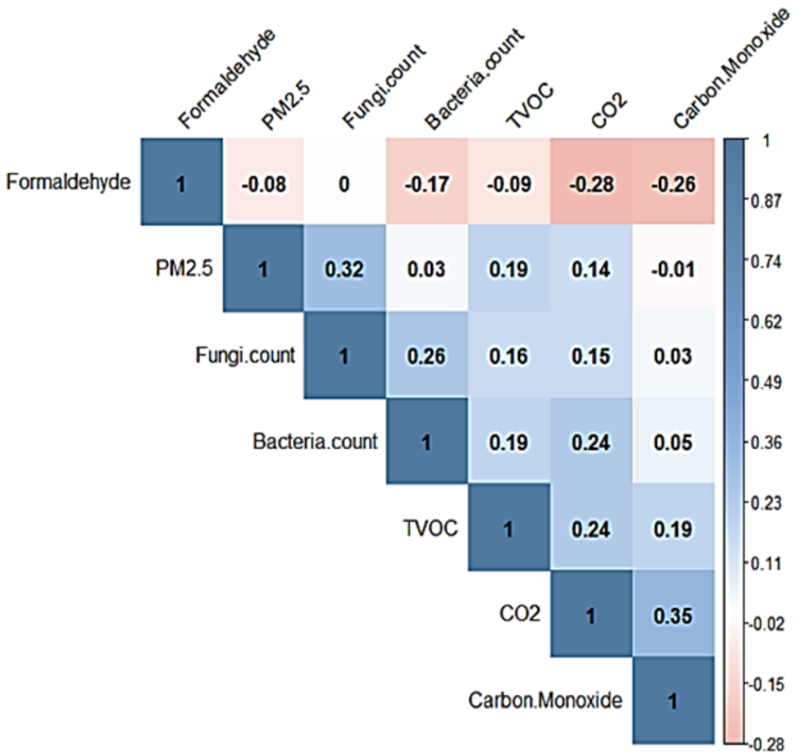


Figure 3-9. The correlation matrix heatmap shows the values of Pearson's product-moment correlation coefficients for all the studied IAQ parameters. The positive coefficients are blue, and the negative coefficients are peach colour. Correlations can range from -1 to +1, where -1 indicates a perfect negative association between variables and +1 indicates a perfect positive association between variables. There is no association between variables when it is 0 (Akoglu, 2018).

3.5.2 Model Formation

Human beings have several variations, such as gender, cultural differences, and expertise, a random variant instead of a single continuum. Therefore, accounting for these variations, participants are modelled as a random variable and correlated within the study conditions without violating the independence of the individual observations. In the mixed model, participants are modelled as a random variable. From section 3.6, the IAQ concentration levels constantly changed, leading to random variability.

It is hypothesized that the cognitive outputs are dependent on the IAQ parameters, and the effect is assumed to be present among all participants. Hence, to satisfy the hypothesis, linear mixed regression models are used (Coster, 2014). The model includes fixed effects (IAQ conditions, the change over time) and random effects (the variability among participants controlled by the fixed effects). Furthermore, linear mixed regression models allow for a hierarchical structure (Van Dongen et al., 2004). Especially when a source could be a source for multiple pollutants, such as carpets could be a source for TVOC and $PM_{2.5}$. Hence the hierarchical structure of the regression model ensures that a source for multiple pollutants does not get embedded into a single Model Z (Equation 3-5).

$$\begin{aligned} Model\ Z\ \leftarrow lmer\big(\boldsymbol{X} \sim PM_{2.5} + TVOC + CO2 + Formaldehyde \\ + CO + Bacteria + Fungi + Scaled\ Week \\ + (1\,|\,PID), data = Y\big) \end{aligned} \tag{3-5}$$

3.5.3 Hierarchical model

The study proposes a non-nested hierarchical modelling approach. Four different mixed regression models were fitted to the data from each cognitive test: Model 0: base model built on covariates (Equation 3-6). Model 1:$PM_{2.5}$ and covariates (Equation 3-7). Model 2: TVOC and covariates (Equation 3-8). Model 3: CO_2 and covariates (Equation 3-9).

$$Model\ 0 \leftarrow lmer\big(\boldsymbol{X} \sim Formaldehyde + CO + Bacteria + Fungi + Scaled\ Week + (1\,|\,PID), data = Y\big) \tag{3-6}$$

$$Model\ 1 \leftarrow lmer\big(\boldsymbol{X} \sim PM_{2.5} + Formaldehyde + CO + Bacteria + Fungi + Scaled\ Week + (1\,|\,PID), data = Y\big) \tag{3-7}$$

$$Model\ 2 \leftarrow lmer\big(\boldsymbol{X} \sim TVOC + Formaldehyde + CO + Bacteria + Fungi + Scaled\ Week + (1\,|\,PID), data = Y\big) \tag{3-8}$$

$$Model\ 3 \leftarrow lmer\big(\boldsymbol{X} \sim CO_2 + Formaldehyde + CO + Bacteria + Fungi + Scaled\ Week + (1\,|\,PID), data = Y\big) \tag{3-9}$$

Where,

X represents data from the EFs test (e.g., reaction time)

Y represents the dataset comprising all the dependent and independent variables accumulated from the study.

The models (Equations 3-7 to 3-9) were fitted using restricted maximum likelihood with participant ID as random intercepts $(1\,|\,PID)$ (to take account of individual characteristics by additively shifting) and weeks (scaled and centred) as random slopes (follow a linear mean trajectory with slope variations). This ensures that any deviation away from the slope is attributed to the effects of the pollutants.

3.5.4 Selection of the Best Fitted Model

The linear mixed regression model that describes how well the model fits the data was determined using Akaike Information Criterion (AIC) from Equation 3-11 (Akaike, 1974).

$$AIC = 2K - 2l \tag{3-11}$$

Where,

K = the number of estimable parameters

l = maximised log-likelihood, measure of model fit

The best fit linear mixed regression model is selected when the model's log-likelihood is maximised. It is maximised when a model is more than two AIC units lower than another model (Posada & Buckley, 2004). AIC cumulative weight expresses the percentage proportion of the total predictive power of the model compared to all other models (Posada & Buckley, 2004). The lowest AIC value and the highest cumulative weight conclude the best fit linear mixed regression model with the least amount of information being lost. It is to be noted that models that satisfy the AIC criteria show a strong association with the IAQ parameters.

Hence, the base model 0 (Equation 3-6), model 1 (Equation 3-7), model 2 (Equation 3-8), and model 3 (Equation 3-9) are compared for the best fit model with AIC in an open-source statistical package R, version 4.1.0, using the function bbmle::AICtab() (R Core Team, 2021). Only the best fit model's statistically significance is discussed further in Chapters 4 and 5.

The residuals are normally distributed and homoscedastic for all linear mixed regression models. Effect sizes based on F tests were calculated from partial eta-squared (see Equation 3-10) using Cohen (1988) interpretation of *f:* *f* = 0.10 is small effect, *f* = 0.25 is a medium effect, and *f* = 0.40 is a large effect. Effect sizes show the size of the difference between the IAQ parameter and X (refer to section 3.5.3).
The analysis was performed in an open-source statistical package R, version 4.1.0, using the function effectsize::cohens_f() (R Core Team, 2021).

$$f = \sqrt{\eta^2 / 1 - \eta^2} \tag{3-10}$$

Where,
$\eta^2 R$epresents the proportion of the total variation in the dependent variable obtained from Linear Mixed Effects model ANOVA.

3.5.5 Multiple Comparison Correction

The study design requires multiple testing with the same data set. When multiple test hypotheses are tested with the same data, the chance of at least one extreme result would be much larger than the p-value, false positives (Nahler, 2009). Hence multiple comparison correction is required. Bonferroni adjustment is used as a posthoc test where the null hypothesis is rejected for each $p_i \leq \frac{\propto}{m}$ while controlling familywise error rate (Weisstein, 2019). Where, p_i is the corresponding p-values, alpha is the significance level and m represent the number of hypotheses. Family-wise error rate is the probability of making false discoveries or type 1 errors associated with multiple hypotheses tests. Among other adjustments Bonferroni adjustment is known to be very strict with false positives (Sedgwick, 2012). Therefore, the adjusted p-value is $^{0.05}/_{4} = 0.0125$. This means less than a 1.25% chance of a false positive being reported.

3.6 Concentration Levels of $PM_{2.5}$, TVOC, and CO_2

The raincloud plots show the concentration levels of IAQ parameters in each of the study rounds under different IAQ condition settings (refer to Figure 3-10 to Figure 3-13). The reference limit from SS 554 (Singapore Standard Council, 2016) was used as an upper bound limit in this study and is represented as a red dotted line in all plots. The outliers present in this data set (from Figure 3-0 to Figure 3-) were *not* removed during the data analysis. This is because the concentration levels of IAQ parameters were reported at an 8-hour average and removing outliers might remove important information about the IAQ parameters. Furthermore, the fluctuations observed in the data reflect the typical phenomena of IAQ. Removing the outliers would mean constraining the data and failing to model the reality. In chapters 4, 5, and 6, the IAQ parameters from all 3 rounds were analysed together (no division of round in the dataset). A t-test for experimental conditions LV and LV* (Figure 3-10 and 3-11) was done with equal variance, showed a difference in the mean.

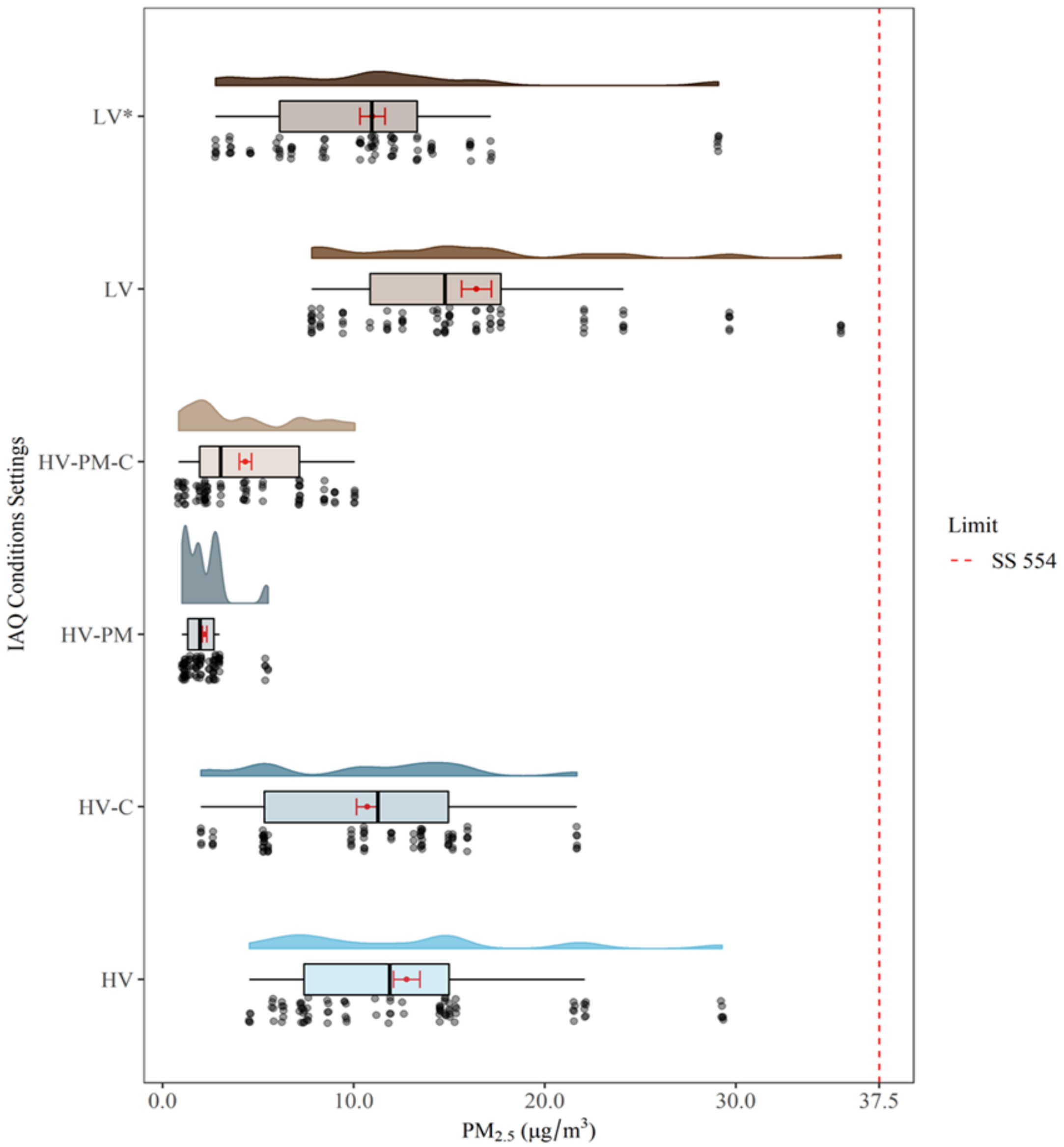


Figure 3-10. Raincloud plot displaying concentrations of $PM_{2.5}$ for different IAQ condition settings for all 3 rounds combined. The plot consists of a probability density plot, boxplot, raw data points and the error bar in red. In the boxplot, the line dividing the box represents the median of the data, the ends of the box represent the lower and upper quartiles, and the extreme lines attached to the box represent the lowest and highest values among the data points, excluding the outliers. The raw data points are at an 8-hour average. The error bar represents mean and standard error of mean (+/- SEM). The red dotted line represents the limit stated in SS 554 (Singapore Standard Council, 2016) from which the study referenced.

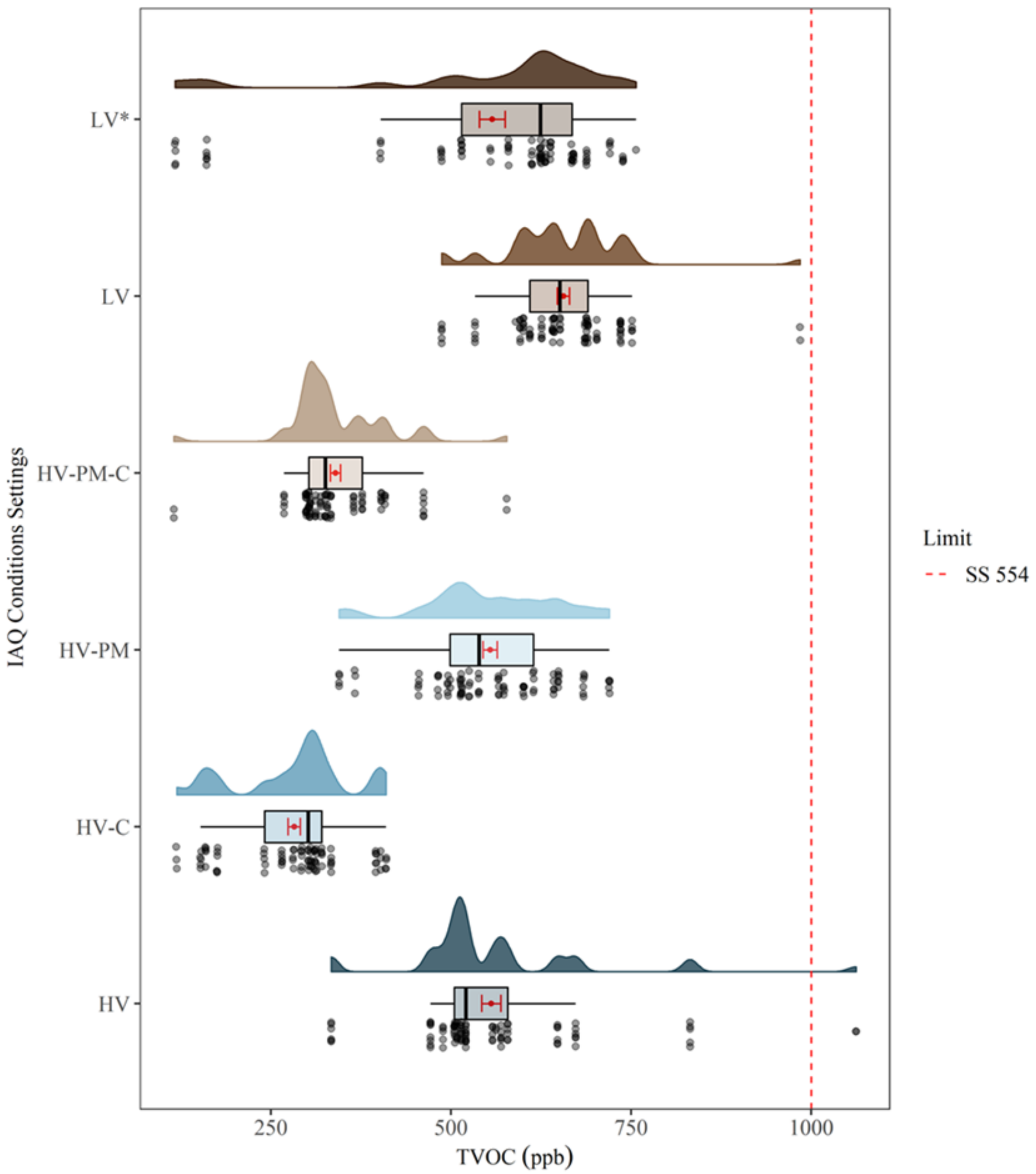


Figure 3-11. Raincloud plot displaying concentrations of TVOC for different IAQ condition settings for all 3 rounds combined. The plot consists of a probability density plot, boxplot, raw data points and the error bar in red. In the boxplot, the line dividing the box represents the median of the data, the ends of the box represent the lower and upper quartiles, and the extreme lines attached to the box represent the lowest and highest values among the data points, excluding the outliers. The raw data points are at an 8-hour average. The error bar represents mean and standard error of mean (+/- SEM). The red dotted line represents the limit stated in SS 554 (Singapore Standard Council, 2016) from which the study referenced. Note: The TVOC data reported in this study is an indicative parameter of the total VOCs used for easy reference.

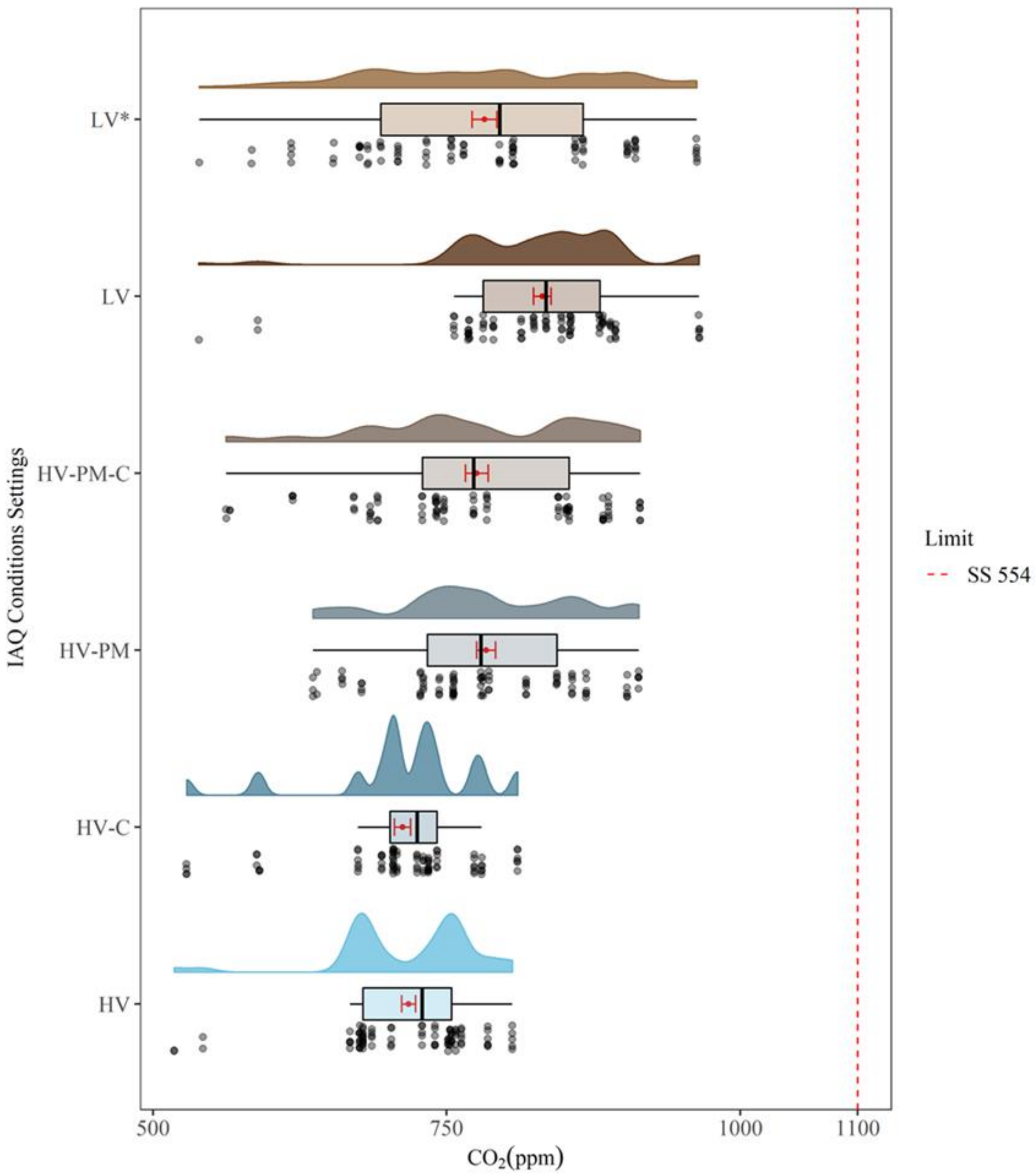


Figure 3-12. Raincloud plot displaying concentrations of CO_2 for different IAQ condition settings for all 3 rounds combined. The plot consists of a probability density plot, boxplot, raw data points and the error bar in red. In the boxplot, the line dividing the box represents the median of the data, the ends of the box represent the lower and upper quartiles, and the extreme lines attached to the box represent the lowest and highest values among the data points, excluding the outliers. The raw data points are at an 8-hour average. The error bar represents mean and standard error of mean (+/- SEM). The red dotted line represents the limit stated in SS 554 (Singapore Standard Council, 2016) from which the study referenced.

3.6.1 Proxy of Bioeffluents

In this study, CO_2 was used as a proxy for the concentration levels of bio-effluents by changing the ventilation rate from 1 ACH to 0.5 ACH (refer to section 2.1.3.2). When the ventilation rate changes from 1 ACH to 0.5 ACH, there is a reduction in fresh air supply. The reduction in fresh air supply increases the concentration of the pollutants in the chamber. This restriction on fresh air supply includes bio-effluents (X. Zhang, Wargocki, Lian, et al., 2017). Therefore, at 0.5 ACH, CO_2 is not a pollutant but rather a proxy of the bio-effluents. The increase in CO_2 concentration levels showed an increase in the bio-effluents such as TVOC, Fungi count and Bacteria count (bioaerosols), as shown in Figure 3-13. Notably, dedicated sampling of bio-effluents and the study of bio-effluent chemical breakdowns were out of the scope of this thesis.

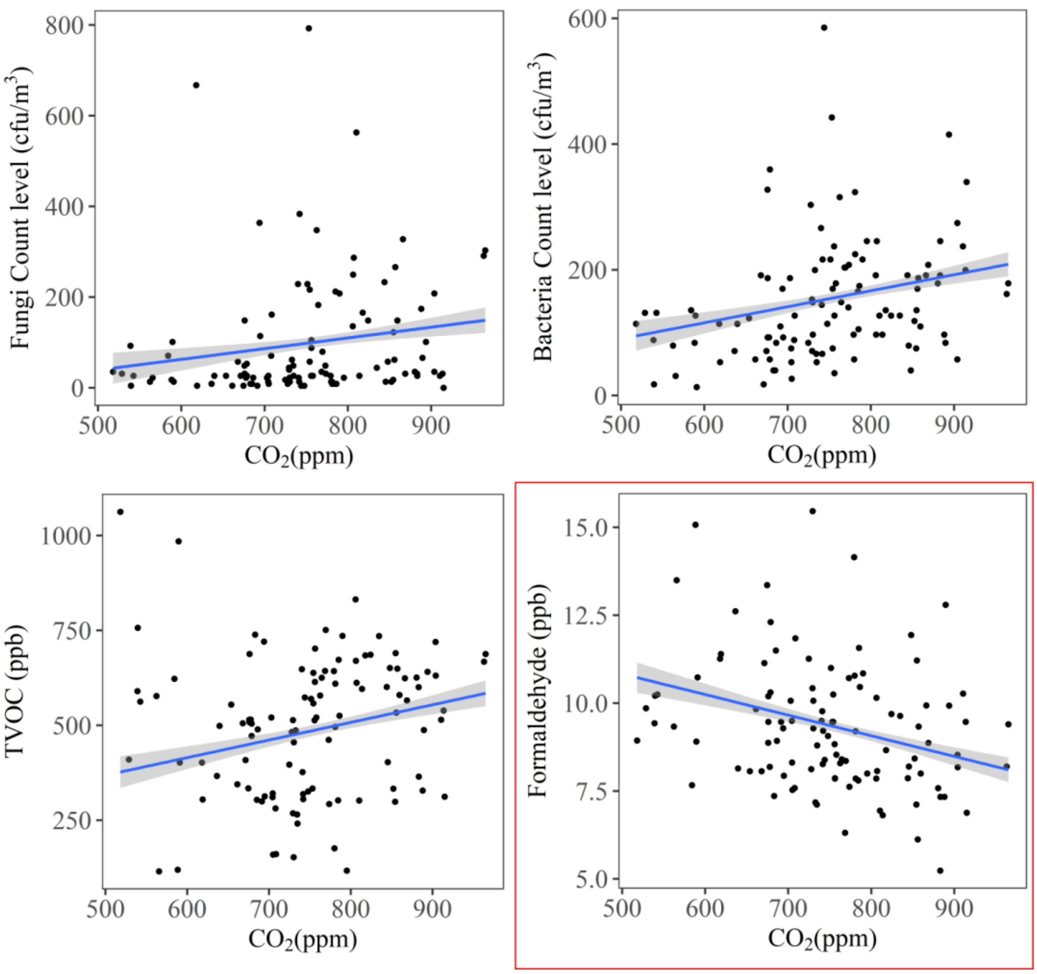


Figure 3-13. Potential bio-effluents (TVOC and bioaerosols) correlate to increased CO_2 levels. However, concentration Levels of formaldehyde are not affected by the increase in the concentration levels of CO_2.

Chapter 4

Impact of IAQ on Creativity

The chapter attempts to investigate the association between IAQ and creativity. Creativity is usually tested using test that simulated divergent thinking. However, the construct of creativity is a combination of divergent and convergent thinking known as lateral thinking. The lack of tests built to simulate lateral thinking was the driving factor to derive to a new methodology called Serious Brick Play (SBP) that simulates lateral thinking. It was based upon on literatures and adaptation of the existing methodology, LEGO Serious Play. The chapter also explains how the qualitative raw data was quantified. It concludes by analysing the association between improved IAQ and creativity.

4.1 Introduction

Creativity is essential to the progress of humanity and economic development. Creativity is involved in everyday thinking through one's ability to restructure and use knowledge in an unconventional way, such as gardening in the backyard to conducting a complicated project. Creativity is an attribute that man uses to solve problems and make decisions that allow humanity to flourish. From an economic perspective, success is usually observed from innovation, an outcome of creative thinking. A study conducted by Edelman Public Relations for Hyper Island (Edelman, 2014) polled over 500 top company executives had endorsed creativity as the second top essential quality for companies to thrive (Menon, 2016). Creativity has never been as relevant as during the COVID-19 pandemic with the increased reliance on technology to keep the economy functioning. For instance, the Ministry of Manpower of Singapore highlighted that creative thinking is among the critical core skills relevant to the future economy (*Critical Core Skills - What They Are And Why They Matter | Education, Career and Personal Development*, 2021).

A common framework for categorising parameters that affect people's creativity is the Four P's model (Person, Process, Press, and Product) (Rhodes, 1961). 'Press' refers to the environment where a task is being performed. Previous research showed how an environment could affect creativity by focusing on physical attributes, e.g., how individuals use the objects present in the environment to solve a problem (Ma et al., 2021). Indoor environment quality (IEQ) refers to the building's performance in terms of quality of acoustic, thermal, visual comfort, indoor air quality (IAQ), health, and well-being of the occupants (J. Kim & de Dear, 2012). Some studies have assessed the influence of IEQ, such as temperature (Martens, 2011), noise (Furnham & Strbac, 2002), and lighting (Lan et al., 2021), on creativity.

4.1.1 Creativity Tests

According to Carroll & Guilford (1968), everyday thinking comprises two creative processes: divergent thinking and convergent thinking. Divergent thinking allows idea generation with vague selection criteria and many possible solutions (Runco, 2012). In contrast, convergent thinking uses persistence and focus on a well-defined problem to find a single solution (W. Zhang et al., 2020). Convergent and divergent thinking can be combined (also known as lateral thinking, which is less discussed and more complex) to allow a set of approaches and techniques to find radically novel approaches to solve problems (Bono & Zimbalist, 1970; Sloane, 2017). Lateral thinking ability represents the full creative potential of an individual. However, most previous creativity studies used divergent thinking to test creativity for open-ended problems (Benedek et al., 2019; Plucker & Runco, 1998) rather than tapping on lateral thinking abilities.

For instance, Carroll & Guilford (1968) employed the Alternative Uses Test (AUT), which required the participant to think of as many use cases as possible for a simple object, a divergent thinking test. Creativity is measured based on the number of use cases generated and how well the participant performs across sub-categories (e.g., fluency, originality, flexibility, and elaboration). The test requires participants to have prior knowledge of different use cases, while different lifestyle, cultural experiences, and questionable psychometric quality introduces partiality in generating the list of uses (Kaufman et al., 2008). Kaufman et al. (2008) highlighted that a major drawback of divergent thinking tests is when the outcome gets overgeneralised to all other aspects of creativity, such as being influenced by participants' prior knowledge. In addition, having a large sample size penalises a response's uniqueness than a small sample size (Silvia et al., 2008) for this test. The Torrance Tests of Creative Thinking (TTCT) is also popularly used to measure divergent thinking, subdivided into verbal and figural components (Baer, 2017).

TTCT involves guessing drawings as part of verbal TTCT and completing a picture as part of figural TTCT. The TTCT test fails to measure the utility of ideation creativity, such as the important cognitive process of insight where the moment of comprehension is used to solve problems (Kaufman et al., 2008; Pretz & Totz, 2007). The AUT and TTCT are based on the concept that creative thinking is stimulated by restructuring and using prior knowledge to generate creative solutions. These conventional tests were designed around divergent thinking but are limited in testing lateral thinking ability.

Lateral thinking involves both divergent and convergent thinking. Smith et al. (Smith et al., 1995a) suggested the principle of knowledge and playfulness, or the imaginative use of knowledge to trigger divergent thinking, as the essential component to simulate creativity. A study that tested participants to solve a mathematics problem while remembering a list of words showed that they could remember more if they used hand gestures for explanation (Goldin-Meadow, 2003). Another study showed that hand gesturing led to better learning (Wagner Cook & Goldin-Meadow, 2006). It is also suggested that using hands to manipulate and construct is a simple way for the brain to use and construct its knowledge of the world (Jabr, 2013). Thus, using hands to gesture and aid in a playful way could potentially unleash creative thinking. Considering the possible link between using hands and creativity, Kristiansen & Rasmussen (2014) described the LEGO SERIOUS PLAY (LSP) method to unleash creativity through a hands-on building process. The method was designed to allow people to express ideas by building objects, which creates a platform for abstract ideas to be more comprehensible. LSP is an open-source methodology made available by LEGO® Group under a Creative Commons licence. LSP is used as a facilitation methodology involving imagination, discoveries, and design opportunities to address enterprise, team, or personal development problems. It further unlocks new knowledge and breaks habitual thinking (Kristiansen & Rasmussen, 2014). The LSP methodology provides a new way to trigger lateral thinking and assess creativity.

4.1.2 Quantification of Creativity

There are numerous methods available to quantify creativity. However, the quantification method chosen should adapt and be feasible to the unique individual construct of the creativity test (Barbot et al., 2019; Glăveanu, 2019; Hornberg & Reiter-Palmon, 2017; Smith et al., 1995b; Sternberg, 2020). Based on the Four P's model of creativity (Rhodes, 1961), an assessment of a 'product' could be narrowed down to three well-known grading systems, namely, the Creative Solution Diagnosis Scale (CSDS) (Cropley & Kaufman, 2012), Consensual Assessment Technique (CAT) (Hennessey et al., 1999) and Creative Product Analysis Matrix (CPAM) (Besemer & O’Quin, 1999), which could be used to quantify the output of the LSP test for creativity. Among the 3, CPAM was a cost-effective method with an easy-to-follow guideline for non-expert judges without compromising the creditability of the quantification process (see Section 4.2.3).

4.2 Methodology

Each participant was given a bag of an equal amount of LEGO ® CLASSIC bricks with colour variations. The compositions of bricks in all bags were similar in numbers for each specific size and specialist bricks (e.g., doors, windows, wheels). The bags of LEGO bricks assigned to the participants were rotated for each week's experiment to ensure that participants were exposed to random selections of bricks to reduce brick familiarity.

4.2.1 LEGO® SERIOUS PLAY® (LSP)

LSP involves a group of people in an association expressing their thoughts and ideas by building three-dimensional models individually with the LEGO bricks provided. They then describe their built significance to other members of the association. LSP is famous for team building, working out the best solution to a shared challenge, strategy development, and unleashing creative thinking. The method involves four steps: challenge, construction, sharing, and reflection. For instance, in a typical LSP session, the facilitator introduces the challenge through related questions. In the construction step, members of the association would individually build a model using LEGO bricks for a specific duration. In the sharing step, members in the association describe their build's significance on how it addresses the challenge (step 1) with other members in the association. In the final step, reflection, the facilitator and other members in the association would reflect on the shared model (step 2) by asking questions, sharing insights, and identifying patterns together with the member (builder). Even though LSP has been used extensively for teambuilding group exercises, the method does not have a quantitative assessment component and cannot systematically assess creativity. However, LSP has the advantages of easy illustrative explanation and a range of solutions to a challenge.

4.2.2 Serious Brick Play (SBP) Design

We proposed the SBP method, an adaptation built upon the LSP methodology to introduce quantifiable lateral creative thinking in participants in this study. Each of the four core steps of LSP was modified to fit into a quantitatively assessed framework.

The key differences and similarities between the two methods are summarised in Table 4-1.

Table 4-1. Core differences and similarities between LEGO Serious Play (LSP) and Serious Brick Play (SBP)

Steps	**LSP**	**SBP**
Challenge	Specialised/specific problem	Global issues
Construction	Individual build	Individual build
	Random bricks	Random bricks
Sharing	Group activity	Individual activity
	Facilitator prompt questions	No prompt questions
	Verbal description	Written description
Reflection	Verbal reflection	Post-test assessment
	Duration	
	2-8 hours	2-8 hours

The first step, challenge, requires a universal problem that caters to the diverse expertise of the participants while not requiring any specialised knowledge to fulfil the task. Global issues of broad emphasis (e.g., climate change) were identified as a suitable theme. However, it is unlikely for all participants to have the same expertise/experience on the topic. Hence to reduce bias caused by different levels of expertise/experience, participants were required to read a document with a comprehensive background summary on the topic. The background information was sourced from various channels, including United Nations Foundations, Worldwide Fund for Nature, National Aeronautics and Space Administration, local newspapers, World Health Organisation Public Health, Mental Health Foundations, and Nature Communications. After reading the challenge carefully, participants were instructed to build their models to express a solution to the challenge (see Appendix C).

In the second step, construction, participants build the model(s) to express their ideas about the solution to the given challenge. For the 6 test weeks, a different challenge was presented (climate change, poverty, mental health, ageing population, air pollution, and biodiversity, see Table 4-2). Participants were instructed not to search for any information or solution online before and while building the model.

Table 4-2. The sequence of given challenges and varying IAQ condition settings

Week	Challenges	Round 1 IAQ#	Round 2 IAQ#	Round 3 IAQ#
0	*Unemployment (Training)*	*HV*	*HV*	*HV*
1	Climate Change	LV	LV	LV
2	Poverty	HV-PM	HV-C	HV-PM-C
3	Mental Health	HV-PM-C	HV	HV-C
4	Ageing Population	HV-C	HV-PM	HV
5	Air pollution	LV*	HV-PM-C	HV-PM
6	Biodiversity	HV	LV*	LV*

#IAQ condition setting: HV – high ventilation (1 ACH), LV – low ventilation (0.5 ACH), PM – PM filter inserted, and C – carbon filter inserted. *Repeated condition

In the third step, sharing, participants describe their model(s) by explaining the choice of colour (if any) and how it was related to the given challenge. Since the nature of SBP was to elicit creativity within individuals rather than a collective group effort, individual participants were asked to document the description instead of presenting it to a group of people like in LSP. Steps 1 to 3 took about 40 minutes to complete (compared to LSP, where a minimum of two hours would be needed). This marked the end of participants' involvement in the SBP design. Besides the written description, photographs of the built models were taken from different views (front, side, back, and isometric view) by the experiment moderator. The photographs were attached to the written descriptions for grading in the next step. In the final step, reflection is a post-test assessment. The post-test assessment involved a panel of random graders to score the models built and the descriptions given by the participants.

4.2.3 Statistical Procedures

Creative Product Analysis Matrix (CPAM) is a three-factor model (Novelty, Resolution, and Elaboration & Synthesis) of creativity (Treffinger, 1981). The 3 factors are expanded to nine facets (Originality, Surprise, Logical, Useful, Valuable, Understandable, Organic, Well-crafted, and Elegant) used to grade creativity. The method was validated by Besemer & O'Quin (1999). Besemer & O'Quin (1999) proved strong support for construct validity when assisted untrained judges make informed judgments following CPAM. In addition to its reliability, it is a cost-effective method.

4.2.3.1 Grading Guidelines Formulation and the Grading Panel

The grading guidelines were formulated based on the CPAM guidelines but catered more toward SBP's methodology. Each factor (novelty, resolution and elaboration and synthesis) in CPAM was translated into a term related to SBP. For example, 'Novelty' from CPAM was translated to 'Originality' in the grading guidelines used in this study (see Figure 4). Originality was broken down into two indicators: usual versus unusual solutions/ideas, which aligned with the SBP methodology. The disagreement about what was considered usual and unusual led the panellists to develop a comprehensive list of usual solutions/ideas for each challenge (see Appendix E). It can be considered unusual when the examining data could not be categorised in the list. 'Fluency' was broken down into two indicators: elaboration and no elaboration. If participants had fulfilled all sub-points under the specified indicator, they would receive a score for elaboration (see Appendix D). 'Build' was split into three levels: sophisticated, normal and no build (i.e., low effort build) as indicators. There was no strict definition for the three levels. Instead, it was left to the graders' discretion since the activity aimed to quantify the participants for their creativity. However, in a dilemma, the graders could refer to the brief guide provided for reference (see Appendix D). With this set of grading guidelines (Figure 4-1), graders could independently grade each data with a minimum of 1 and a maximum of 5.

Hypothesis	Description	Facets	
Novelty	Newness in materials, processes, concepts and methods of making the product	• Originality • Surprise	➡ **Originality**
Resolution	Aspects of how well the product functions	• Logical • Useful • Valuable • Understandable	➡ **Fluency**
Elaboration and Synthesis	The style used in the product production	• Organic • Well-crafted • Elegant	➡ **Build**

Originality		
Score	Unusual Uses	Usual Uses
	2	1

Fluency		
Score	Elaboration	No Elaboration
	1	0

Build			
Score	Sophisticated Build	Normal Build	No Build
	2	1	0

Figure 4-1. Details on how CPAM was adapted to Serious Brick Play (SBP) methodology to establish grading guidelines. Each criterion's facets of CPAM are summarised into a factor applicable to SBP that is further broken down into gradable indicators.

4.2.3.2 Test and Validation of the Grading Panel

The grading panel consisted of 7 randomly selected adults who had no prior knowledge of SBP. Structured training was given to the panel to familiarise themselves with SBP and the grading guidelines (refer Figure 4-1). The robustness of the grading guidelines was tested with 20 trial samples (from week 0) from the same population for the panel to score. The validity of the grading guideline is determined by testing the inter-rater reliability using Intra-Class Correlation (ICC). ICC is an index that reflects the degree of correlation and agreement between measurements (Koo & Li, 2016). The assessment was done with the total scores obtained from each grader. ICC is determined using equation 4-1 (Hallgren, 2012).

$$X_{ij} = \mu + r_i + e_{ij} \quad (4\text{-}1)$$

X_{ij} = Rating provided to participant I, μ represents the mean of the true score for variable X

r_i = Deviation of the reuse score from the mean for participant I

e_{ij} = Measurement of error

The ICC model used is a two-way model with type as consistency. The interpretation of the ICC estimate is based on the lower bound, 95% confidence interval; values of ≤ 0.50, > 0.50 and ≤ 0.75, > 0.75 and ≤ 0.90 or > 0.90 were classified as poor, moderate, good, and excellent reliability, respectively (Koo & Li, 2016). This indicates the degree of agreement among the graders.

The grading panel was kept blind about the overall experimental design. This prevents bias scoring. The best-scored build and the worst scored build averaged across the grading panel, closely following the guidelines, is shown in Figure 4-2.

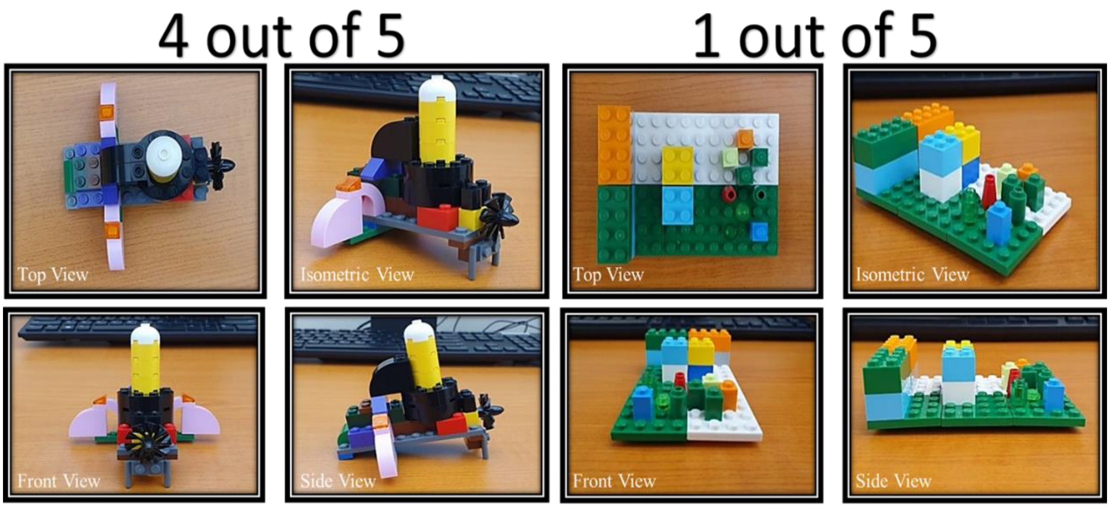


Figure 4-2. Examples of build scored the highest and lowest points according to the SBP guidelines. The build was randomly selected across 522 data points. Thus, the score represents the average score across the 7 graders.

4.3 Results

Analysis was done with data collected from 87 participants. An equivalent of 3 participants' worth of data points (18 invalid data points) was removed from the dataset due to minor technical issues (such as missing photos of the built) that occurred during the experiment. Hence, 522 data points, one data point comprised of built model pictures and a participant's description of the model (s), were analysed.

4.3.1 Grading Panel Agreement Analysis

The ICC coefficients were estimated separately for each of the three experimental rounds to assess inter-rater reliability. ICC allows the measurement of the strength of inter-rater agreement for ordinal scales. Thus, a high ICC indicates high similarity between panellists. The psych::ICC () function in R (version 4) was used to compute ICC estimates and their 95% confidence interval (CI) based on a mean-rating (k = 7), absolute agreement, and the two-way random-effects model. Based on the lower bounds of 95% CI, as summarised in Table 4-3, the level of reliability of the three rounds of experiments ranges from "moderate" to "good" (Koo & Li, 2016). Hence, this states that the inter-reliability is at moderate to good agreement, allowing the graders to grade each data point. The mean score across the 7 graders was taken as the final creativity score per participant.

Table 4-3. Results of ICC calculation for Inter-Rater Reliability. The same set of graders scored all data points for the two-way random effects model based on a mean of 7 graders to determine the absolute agreement.

Round	**ICC**	**95% Confidence Interval**		**F Test with True Value 0**			
		Lower Bound	Upper Bound	Value	d*f* 1	d*f* 2	p-value
1	0.79	0.72	0.83	6.2	251	1506	<0.001*
2	0.77	0.72	0.81	5.1	251	1506	<0.001*
3	0.8	0.76	0.83	5.6	241	1446	<0.001*

*denotes statistical significance for p-values less than 0.0125, after the Bonferroni adjustment.

4.3.2 Hierarchical Regression Model

Table 4-4. Linear mixed regression model testing the effect of IAQ parameters on creativity scores and treating participants as a random intercept.

	Model Parameters	**Model 0**	**Model 1**	**Model 2**	**Model 3**
Scaled Week	Standardised estimate	-0.03	-0.04	**-0.04**	-0.06
	95% standard confidence interval	[-0.06, 0.001]	[-0.08, -0.01]	**[-0.07, -0.01]**	[-0.09, -0.02]
	p-value	0.09	0.01*	**0.02**	0.001*
	Effect size	0.03	0.05	**0.05**	0.06
Fungi	Standardised estimate	0.03	0.05	**0.04**	0.02
	95% standard confidence interval	[-0.01, 0.06]	[0.01, 0.09]	**[0.01, 0.08]**	[-0.01, 0.06]
	p-value	0.17	0.02	**0.02**	0.23
	Effect size	0.03	0.05	**0.04**	0.02
Bacteria	Standardised estimate	- 0	-0	**0.03**	0
	95% standard confidence interval	[-0.04, 0.03]	[-0.05, 0.03]	**[-0.01, 0.06]**	[-0.03, 0.05]
	p-value	0.68	0.63	**0.13**	0.62
	Effect size	0	0	**0.03**	0
Formaldehyde	Standardised estimate	-0.11	-0.11	**-0.09**	-0.11
	95% standard confidence interval	[-0.15, -0.07]	[-0.15, -0.07]	**[-0.13, -0.05]**	[-0.15, -0.07]
	p-value	<0.001*	< 0.001*	**< 0.001***	< 0.001*
	Effect size	0.10	0.10	**0.08**	0.10
CO	Standardised estimate	- 0	-0	**0.03**	0.03
	95% standard confidence interval	[-0.04, 0.03]	-0.04, 0.03	**[-0.01, 0.06]**	[-0.01, 0.06]
	p-value	0.77	0.74	**0.11**	0.14
	Effect size	0	0	**0.03**	0.03
$PM_{2.5}$	Standardised estimate		-0.06		
	95% standard confidence interval		[-0.09, -0.03]		
	p-value		< 0.001*		
	Effect size		0.07		
TVOC	Standardised estimate			**-0.15**	
	95% standard confidence interval			**[-0.18, -0.12]**	
	p-value			**< 0.001***	
	Effect size			**0.17**	
CO_2	Standardised estimate				-0.11

	95% standard confidence interval				[-0.15, -0.07]
	p-value				< 0.001*
	Effect size				0.10
AIC		3975.8	3976.8	**3913.8**	3967.9
AIC Weightage		0%	0%	**100%**	0%

*denotes statistical significance for p-values less than 0.0125, after the Bonferroni adjustment.

From Table 4-4, the best fitted model 2, with an AIC value of 3913.8 (the lowest among other models), carried 100% of the cumulative weight (highest possible AIC weightage) was used for interpretation. The model intercept (fixed variables = 0) is at 2.81 (95% CI [2.59, 3.02], t (2777) = 25.47, p < .001).

Further examination of Model 2 showed a highly significant negative effect of TVOC on creativity scores (standardised beta = -0.15, p <0.001) with a small effect size. The linear relationship between creativity and TVOC is depicted in Figure 4-3, where a 10% decrease in TVOC levels is associated with an improved creativity score of 1.5% (obtained from the statistical estimate).

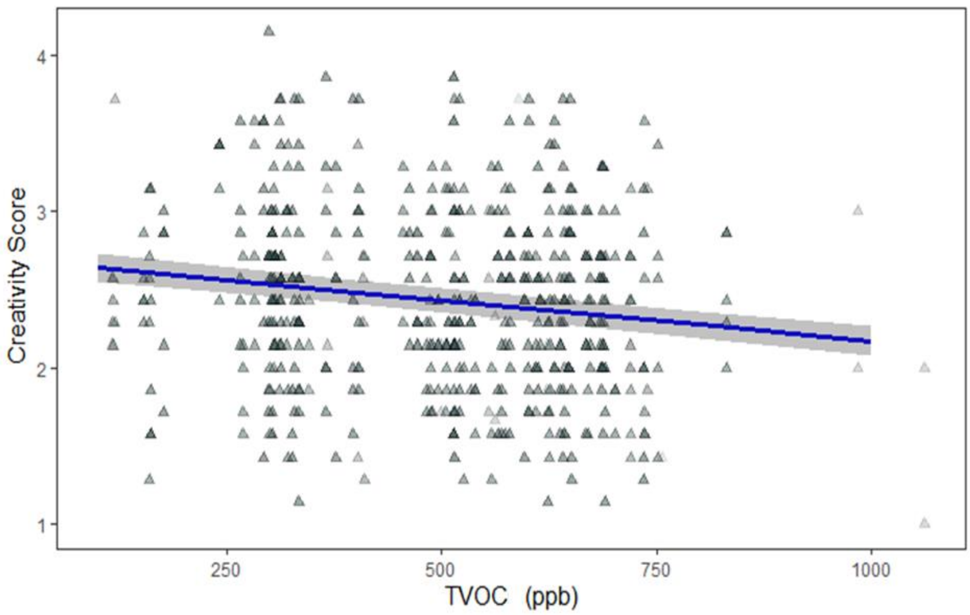


Figure 0-3. Effect of TVOC on creativity score in Model 2. The shaded band represents a confidence interval of 95% of the data. The small triangles represent data points along with the regression line.

4.4 Discussion

Creativity is an essential cognitive ability that affects daily lifestyle choices and economic progression. Among the factors that affect creativity, it is also important to note that the environment where creativity is stimulated plays a key role. Previous studies had discussed the optimum physical attributes of an ideal creative environment but lacked the examination of IAQ and the effects on an individual's full creative potential (Kwallek & Lewis, 1990; McCoy & Evans, 2002; Shalley & Gilson, 2004). The data from our study suggests that relatively low concentrations of TVOC in the environment (within international standards) can impact an individual's creative potential. For example, a 50% increase in TVOC concentration levels due to common sources, like perfume, air freshener, and aroma diffusers, would bring about a 7% decline in creativity.

Choi et al. (Choi et al. 2014) highlighted the notion of Henri Poincaré (1854-1912), a French mathematician who went into the forest for creative motivation to find solutions to his mathematical problems. Similarly, the results from this study potentially showed that one underlying aspect of an environment that can affect creativity is the chemical concentration of the pollutants. Instead of changing the physical attributes of the environment, improving the air quality could be an economical solution to improve occupants' creativity. These results build upon the existing work by Allen et al. (2016), where low TVOC and CO_2 were reported to affect occupants' executive cognitive functions in an enclosed environment.

The study examined undergraduate and postgraduate students only, thus skewed towards a young, educated population. Further work could be extended to different age groups, such as the elderly and children. However, the building challenge might need to be modified for these age groups. In addition, the IAQ data from this study is relatively low. Hence the delta between the filter conditions and 0.5 ACH conditions is not large. This could have masked the potential effects of $PM_{2.5}$ and may have limited the effects of TVOC.

Studies have utilised tests dedicated to stimulating divergent thinking to understand the mechanisms of creative thinking. However, the main disadvantage of divergent thinking creativity tests is using prior knowledge, which holds a bias element over diverse cultures and experiences across different individuals. The bias element hinders the accuracy of assessing the divergent thinking ability of an individual. Therefore, this thesis established a neutral ground to assess creativity through the implementation of SBP through three core steps (Read, Build, and Describe). The test neutralises the bias element observed in previous creativity tests by providing participants with the same insights into the building challenge from a global to a local perspective. Hence, we introduced SBP coupled with a robust grading system that aided in realising one's full creative potential through the mode of lateral thinking.

Part of the SBP methodology involves rotating the set of bricks across participants for each building challenge, such that participants would receive a different set of bricks each week. Each set of bricks contained similar items to the other sets but could vary in colour, size, and shape. This minimises the chance of repeatability of structures and familiarity with the brick set. However, the different variations of bricks between the sets could affect participants' ideas on the challenges. Therefore, each participant could be assigned a unique building challenge (instead of the same building challenge across all participants in each week) along with the set of bricks that would be rotated over the weeks instead. Alternatively, a more extensive standardised set of bricks could be used throughout the different conditions.

The qualitative output (built photos and description) of SBP was graded with seven random graders, with a guideline modified from CPAM to suit SBP's core steps. The modification of CPAM was required because creativity is not a unitary measure, and the quantification should match the methodology and theoretical aims of research that are unique to the study (Glăveanu, 2019). The guideline went through a few iterations to ensure its robustness to cater to different building challenges.

The generalisability of the results is limited by the type of building challenge, the colour of bricks, the age group of participants and the outdoor air quality of the nation involved. The building challenge was based on popular global issues to establish neutral grounds for participants from different backgrounds and experiences. Suppose studies were to adopt SBP and modify the building challenge according to their research needs if the existing SBP is not aligned with participants' competence. In that case, it is vital to choose a challenge in line with the participants' competence (neither too easy nor too difficult). A guide would be the flow concept. Flow is a condition characterised by complete absorption in what one does, operating to one's full potential (Nakamura & Csikszentmihalyi, 2009). Anxiety can result if the challenge is too difficult for an individual's ability. If the challenge is too easy, the individual can become bored. An ideal state is achieved when the challenge level is calibrated to the individual's competence, encouraging effective learning and well-being. Engaging in play is one of the ways to reach this ideal state, like SBP.

4.5 Conclusion

Creativity, a complex set of idea-generating or imagining behaviours encompassing numerous sub-processes of the brain, is tested chiefly across numerous studies by surveying an individual's divergent thinking ability. By modifying the SBP paradigm, LSP breaks habitual thinking with hands-on learning through LEGO bricks. The qualitative output is then graded to quantify participant responses. Within this study, the SBP paradigm was used to test the impact of IAQ on creativity, where reducing the TVOC concentration showed an increase in creativity score. However, reduction in $PM_{2.5}$ and high ventilation rate did not show any statistical significance.

Chapter 5

Impact of IAQ on Cognitive Functions

The chapter investigates the controlled exposure of $PM_{2.5}$*, TVOC and* CO_2 *as the bio-effluent on participants' cognitive functions in an office-like environment. The 8-hour long single-blind experiment concludes with a cognitive test battery. The cognitive test battery tested critical cognitive functions classified in an 'umbrella' term executive function (EFs): working memory, inhibitory control, cognitive flexibility & control, speed of information processing, planning, and fluid intelligence. The chapter analyses each task administered with different variations tested for statistically significant, and only statistically significant results are presented.*

5.1 Introduction

From Chapter 2, it is evident that negative intervention to IAQ influences cognitive abilities. This chapter explores one of the mitigation methods as a positive intervention to IAQ to reduce indoor air pollutants ($PM_{2.5,}$ TVOC, and CO_2 (bio-effluents)). The typical practice adopted by most non-residential buildings is implementing particulate filters (reduction in $PM_{2.5}$) in the air-conditioning and mechanical ventilation (ACMV) system. According to Building and Construction Authority (2016), the criterion for green buildings is to be equipped with filters of at least the MERV 13 rating (ASHRAE Standard, 2017). A previous study showed that air filters (MERV 5) improved employee performance by 9% at a ventilation rate of 20 L/s/p (Wargocki et al., 2004). Unlike $PM_{2.5}$, TVOC is a molecular pollutant that is too small to capture by particle filters. Therefore, to reduce TVOC, molecular filters that use activated carbon as an active ingredient (also known as carbon filters) are used. However, limited studies use particle filters as an invention means to study the effects on cognitive abilities.

The study was inspired by the lack of understanding and inadequate emphasis on air filters in the ACMV systems. Along with the possibility of affecting the occupant's cognitive abilities. The study investigates the effects of air filters in the ACMV system (MERV 14 and carbon filter) on executive cognitive function among 90 young adults (20-35 years) in an office-like environmental chamber over a collective of 21 weeks administered over 3 rounds. Participants were blind to the study conditions.

5.2 Methods

This chapter focuses on the IAQ parameter effects observed through the responses from the cognitive test battery (PEBL). Figure 5-1 recaps the daily protocol the participants adhered to, the proposed structure for executive functions (EF), and the IAQ study conditions they were exposed to for 6 analysable weeks. Week 0 was training week. PEBL was administered in one seating with no breaks allowed in between. Hence, the effects of employing an EEG headset are discussed in Chapter 6.

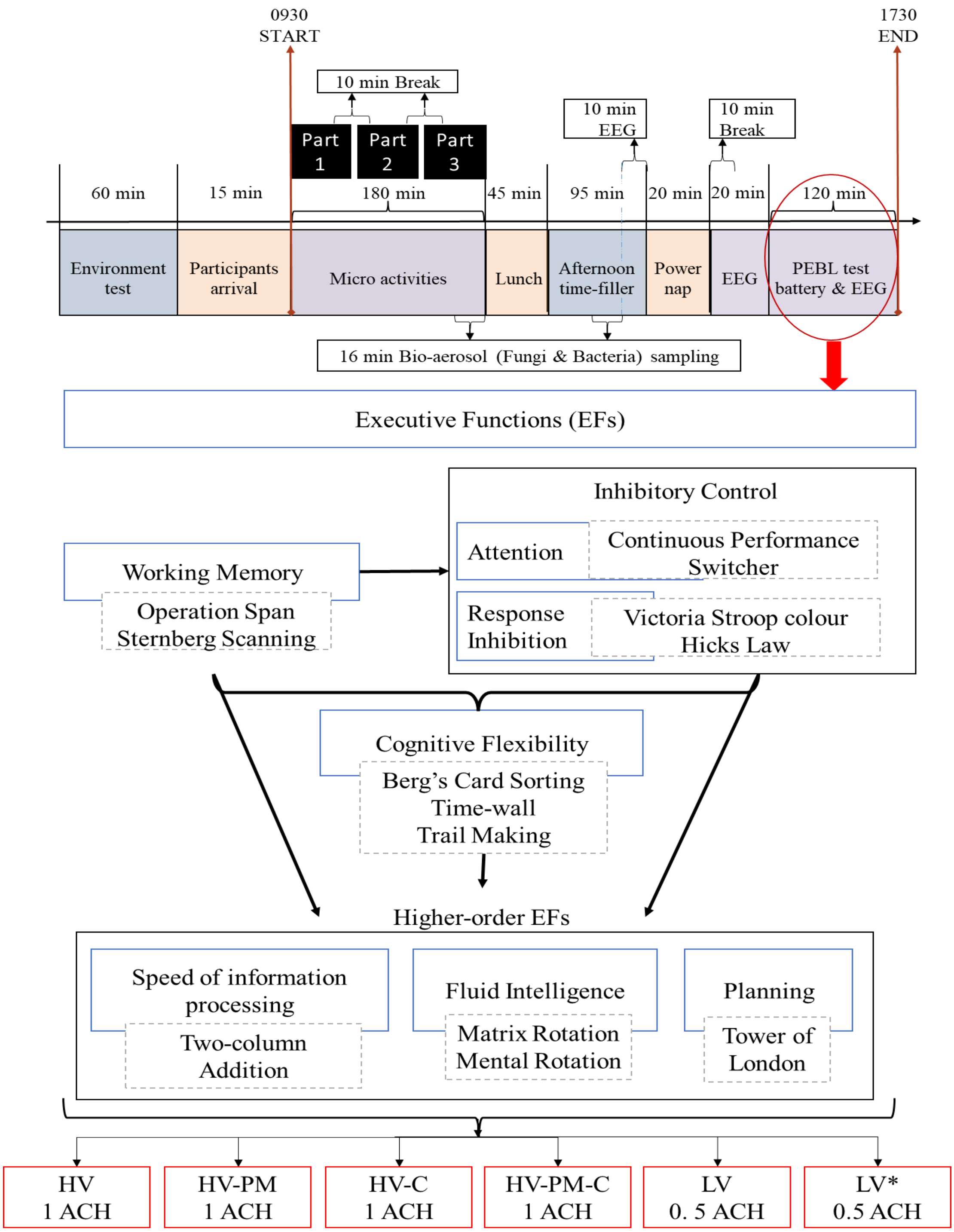


Figure 5-1. Participant daily protocol. Adapted from section 3.4.2, highlights when PEBL test battery was administrated, indicated by the red arrow and the corresponding IAQ study conditions (HV – high ventilation (1 ACH), LV – low ventilation (0.5 ACH), PM – PM filter inserted, and C – carbon filter inserted) in red boxes.

5.2.1 PEBL Test Battery

The breakdown of the task from the PEBL test battery that conforms to the proposed EF structure (see chapter 2, section 2.4) is shown in Figure 5-1. This section elaborates on the list of tasks done under 7 categories of executive cognitive functions. All practice trials administered as a default by the battery were removed from data analysis. Trials here refer to a different task within a test battery. Test here refers to the test battery.

5.2.1.1 Matrix Rotation Test

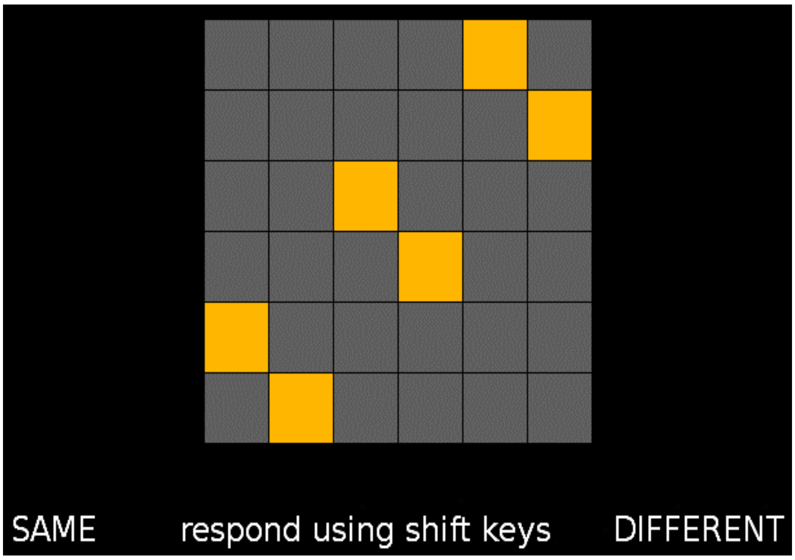


Figure 5-2. Screenshot of Matrix Rotation from PEBL test battery (Mueller & Piper, 2014)

The matrix rotation test is a version of a task from UTC (unified tri-services cognitive performance assessment battery) test battery (Perez et al., 1987). It required participants to mentally rotate a visual grid (six by six), shown in Figure 5-2, to determine whether the matrix before the rotation was the same after the rotation. The response matrix could have been either the same as or different to the target matrix. Participants were required to respond by pressing the 'shift' key on either side of the keyboard to the stimuli (see Figure 5-2 for reference). The key functional cognitive abilities utilised were selective attention, working memory and visual processing (Mueller, 2010).

5.2.1.2 Mental Rotation Test

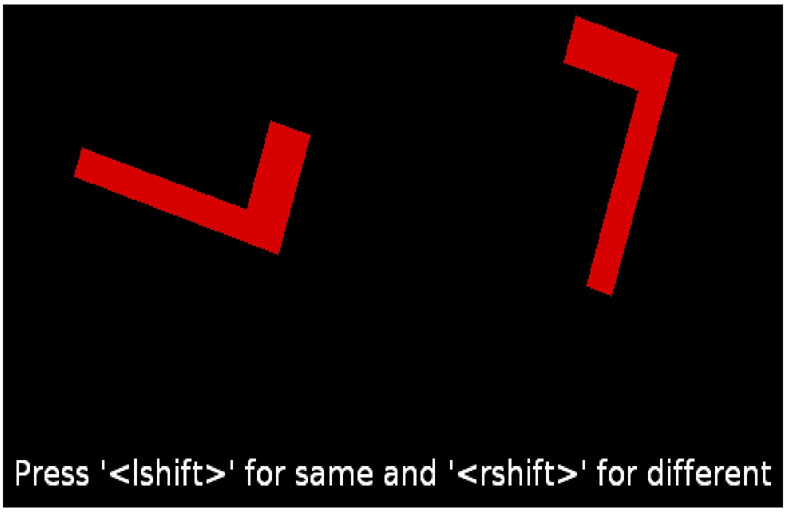


Figure 5-3. Screenshot of Mental Rotation from PEBL test battery (Mueller & Piper, 2014)

The mental rotation test is known as Shepard's mental rotation test (Berteau-Pavy et al., 2011). It requires participants to rotate a polygon shown in the screen in their minds to determine whether the two figures are identical. Participants were required to respond by pressing the ‘shift’ key on either side of the keyboard to answer if the figures on the screen (see Figure 5-3) were identical and rotated or mirrored and rotated. The key skills utilised were reasoning, visual processing, and decision making (Mueller, 2010).

5.2.1.3 Time-Wall Test

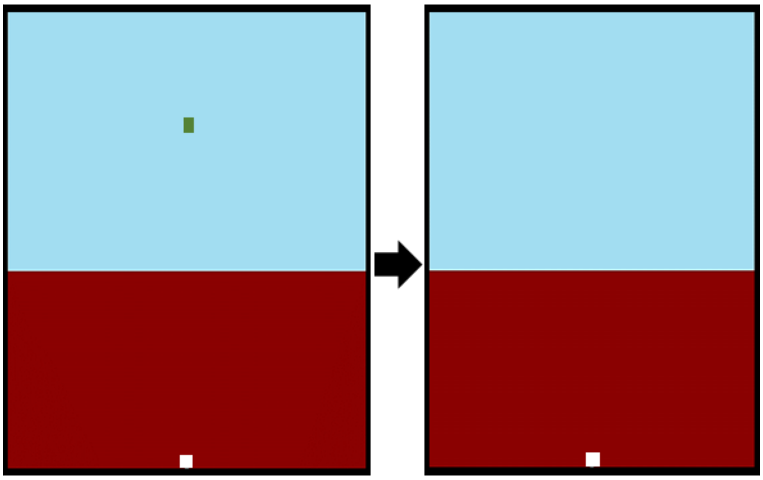


Figure 5-4. Screenshot of Time-wall from PEBL test battery (Mueller & Piper, 2014)

The time-wall test is a version of a task from UTC (unified tri-services cognitive performance assessment battery) test battery (Perez et al., 1987; Snyder & Rice, 1990). It assesses the ability to estimate the time when a moving target (green block Figure 5-4) would reach the destination (white block in Figure 5-4) behind the red wall. Participants are required to respond by pressing the space bar to the stimulus. Since participants must constantly track the dropping object after its disappearance (behind the red wall), it requires them to imagine the location of the moving target using an estimation of the moving target's speed. This allows the assessment of motion perception and prediction of a pattern (Piper et al., 2012). A notable aspect of performance on this test is that it has a stable characteristic. The key skills utilised were reasoning, calculating, reaction time, strategy, and problem-solving (Mueller, 2010).

5.2.1.4 Tower of London Test (TOL)

Figure 5-5. Screenshot of TOL-R from PEBL test battery (Mueller & Piper, 2014)

The tower of London (TOL) test is a traditional problem solving and planning test involving a virtual tower puzzle. Several versions of the TOL-R have been implemented in the literature, and the software used in our study. For this study, participants were given the Schnirman et al. (1998) version, which included the constraints of a maximum of three pile heights, three disks with four restricted clicks and under 2 minutes to solve each of the 30 trials, as shown in Figure 5-5. If either limit exceeds, the participant fails to complete the trial. Hence, the test requires the participants to make and follow plans which require both strategy and problem-solving skills to complete the test. The key skills utilised were strategy and problem solving, colour processing, forming and retaining, planning, and hand-eye coordination (Mueller, 2010; Piper et al., 2012).

5.2.1.5 Berg's Card Sorting Test (BCST)

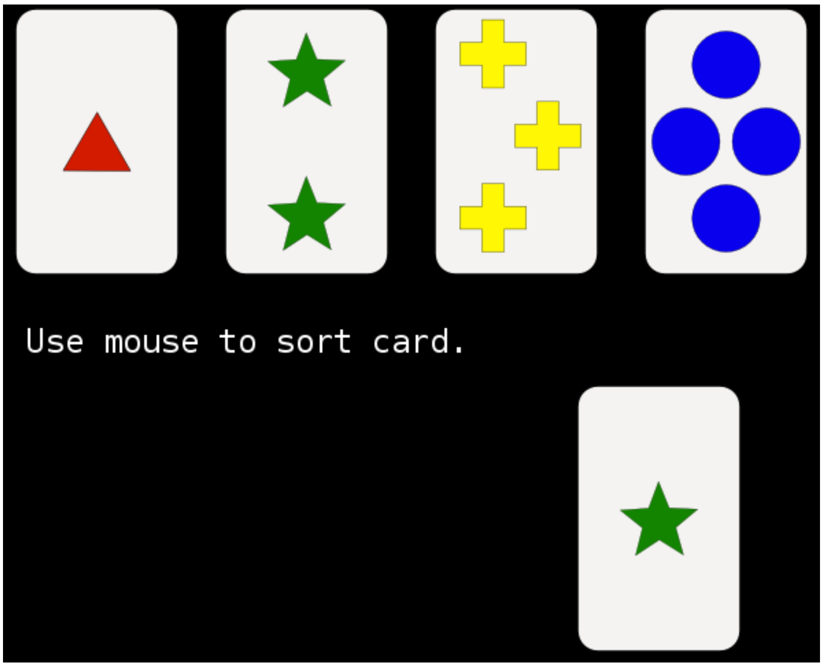


Figure 5-6. Screenshot of BCST from PEBL test battery (Mueller & Piper, 2014)

Berg's card sorting test (BCST) is a version of Berg's Wisconsin card sorting test (Berg, 1948). According to an unknown and changing rule, the test required participants to sort multi-attribute cards into the given piles on the top row (see Figure 5-6). The changing rule could be any matching; shape, colour, or number. Participants were required to determine the new rule and anticipate the changing rule accurately. The key skills used were strategy and problem solving, decision making, inhibition, and working memory (Mueller, 2010).

5.2.1.6 Switcher Test

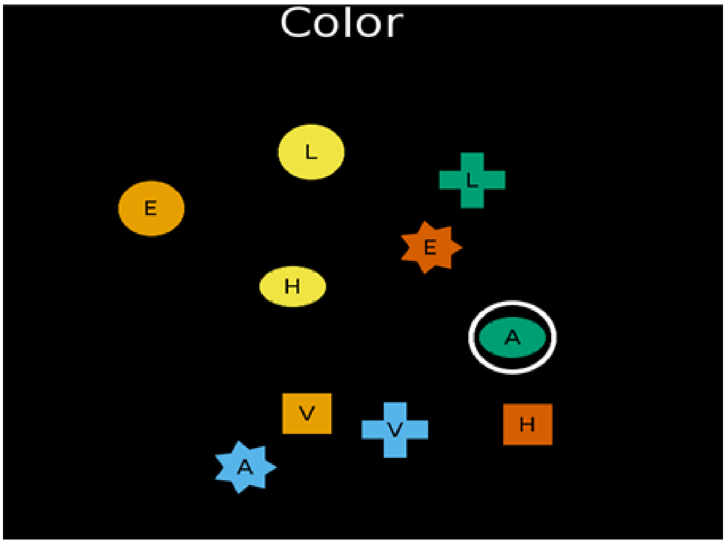


Figure 5-7. Screenshot of Switcher test from PEBL test battery (Mueller & Piper, 2014)

The switcher test involves searching and matching objects with rules that are based on a changing stimulus dimension of the previous target (Anderson et al., 2012). The test uses three stimuli rules: colour, shape, and letter. The stimulus rule is shown at the top of the screen (see Figure 5-7). Participants are required to complete 12 trials with three different test type sequences: two consistent stimuli (e.g., rule switches between colour or shape), three consistent stimuli (rule switches between colour, shape, or letter in order) and a random sequence utilising three stimuli (rule switches between colour, shape, or letter in a random way). The key skills used were visual processing and selective attention (Mueller, 2010).

5.2.1.7 Two-column Addition Test

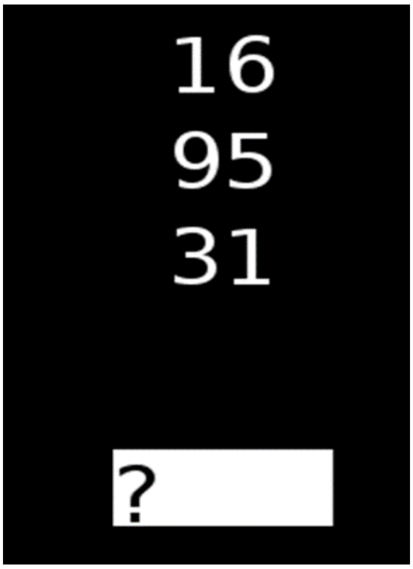


Figure 5-8. Screenshot of Two-column from PEBL test battery (Mueller & Piper, 2014)

The two-column addition test requires participants to do a mental arithmetic summation of a three, two-digit addition (Figure 5-8) (Perez et al., 1987). The test comprised 45 trials with no time limit imposed. Participants were expected to respond quickly and accurately. The key skills used were mathematical processing and working memory (Mueller, 2010).

5.2.1.8 Hicks Law Test

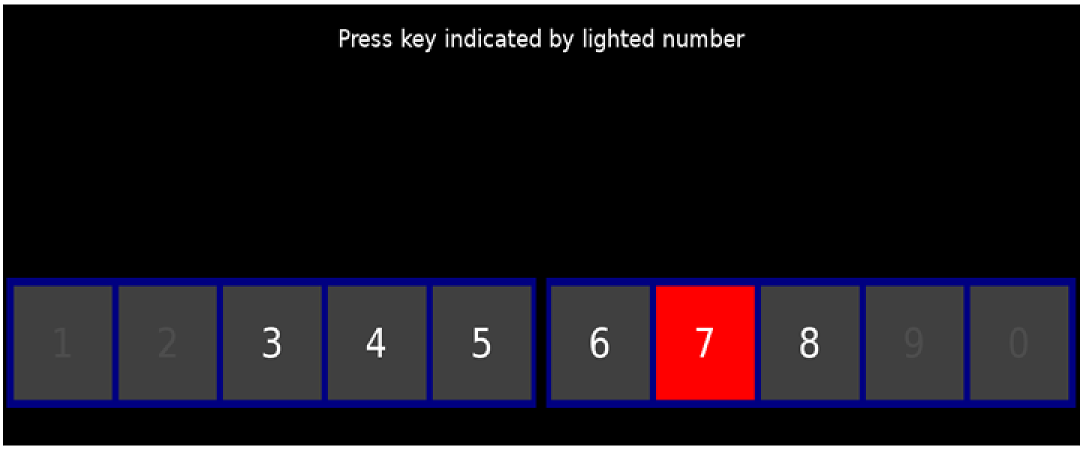


Figure 5-9. Screenshot of Hicks Law test from PEBL test battery (Mueller & Piper, 2014)

Hick's law (increase in the number of response choices, increases the decision time logarithmically) predicts the time to press the correct highlighted key for the number of choices present (Hick, 1952; Proctor & Schneider, 2018). The test required the participants to respond to the stimuli (flashing numbers boxed in red) in the same sequence observed from the screen (Figure 5-9). Participants were required to finish 50 trials of 8 variations (i.e., 5, 56, 567, 4567, 45678, 345678, 3456789, and 23456789). The ability to respond to the stimuli was determined by response time for correct response. The key skills used were response inhibition and coordination (Mueller, 2010).

5.2.1.9 Trail making Test

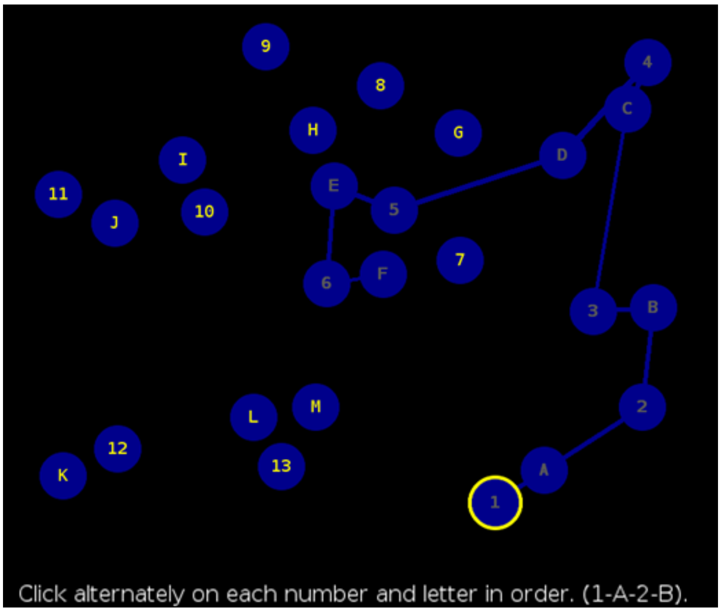


Figure 5-10. Screenshot of Trail making test from PEBL test battery (Mueller & Piper, 2014)

The trial-making test is about connecting the dots (both in numeric and alphabets, see Figure 5-10) accordingly in an order such as 1-2-3 (Piper et al., 2012). The order changes between numeric (1-2-3), alphabetical (a-b-c) or combination of both (1-a-2-b-3-c). Participants were required to click on the dots (targets) to connect a set of 26 dots while maintaining accuracy. The key skills utilised were language processing, numerical processing, visual attention, test switching, speed of processing, mental flexibility and hand-eye coordination (Arnett & Labovitz, 1995; Mueller, 2010).

5.2.1.10 Victoria Stroop Test

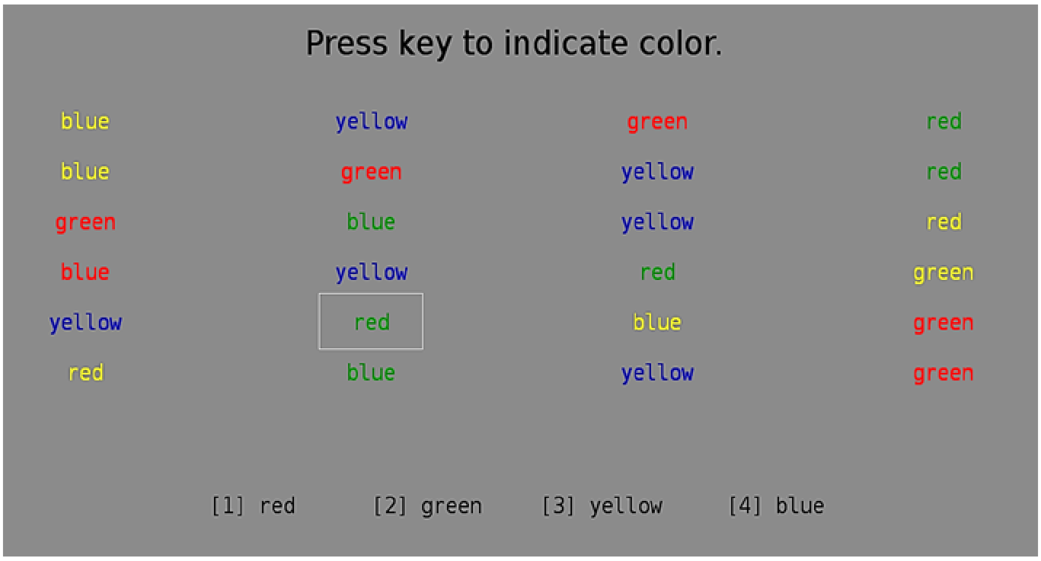


Figure 5-11. Screenshot of Stroop-Vic from PEBL test battery (Mueller & Piper, 2014)

The Victoria Stroop Colour test required the participants to respond to the name or the colour of the stimuli (Troyer et al., 2006). Participants were required to complete 24 trials for each variation. There were a total of three variations arranged in blocks, namely, coloured dots – block 1, coloured words ('hard', 'when', 'and', and 'over') – block 2, and coloured words describing colours – block 3 as shown in Figure 5-11. Participants need to respond to the colour of the items or words, not the meaning of the words themselves (e.g., the word "red" coloured in green would be responded to with "[2] green"). Incongruent stimuli (where the colour of the text, e.g., green, clashes with the meaning of the text, e.g., red, will require the participant to inhibit their automatic response. The key skills used were response inhibition and selective attention (Mueller, 2010).

5.2.1.11 Continuous Performance Test

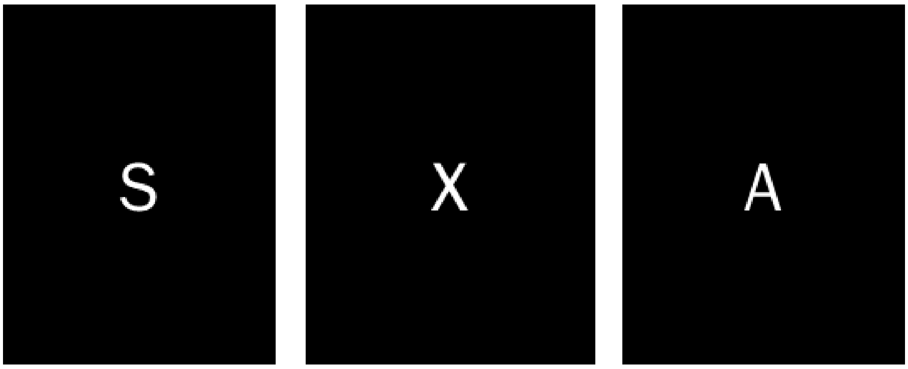


Figure 5-12. Screenshot of PCPT from PEBL test battery (Mueller & Piper, 2014)

The continuous performance test is a vigilance test which requires participants to respond to a continuously presented stream of visual stimuli (Piper et al., 2012). The test is divided into blocks with no variations between the blocks. Each block consists of 20 trials of 360 letters (at approximately 2.54 cm in the centre of the screen) presented one at a time. Participants must respond to all visual stimuli by pressing down the ‘spacebar’ key on the keyboard except for the 'X' stimuli (see Figure 5-12). The probability of an ‘X’ present was kept at the default of 0.1 (10% of the stimuli). The key skills used were concentration and attention (Mueller, 2010).

5.2.1.12 Operation Span Test

Figure 5-13. Screenshot of Operation Span from PEBL test battery (Mueller & Piper, 2014)

The operation span is a memory test that alternates between a mathematical problem (a distracter) and a letter sequence (memory) trial (Mueller & Piper, 2014). Participants were required to solve the mathematical problem while remembering the letters flashed one at a time before and after a mathematical problem. At the end of the given sequence, participants recalled the letter sequence (see Figure 5-13). The sequence starts with two letters (easy) and goes up to seven letters (difficult). The distracter has a time limit of 4 s, and the letters were timed for 1 s. Participants were required to answer and remember the sequence within the time limits. The key skills used were working memory and numerical processing (Mueller, 2010).

5.2.1.14 Sternberg Scanning Test

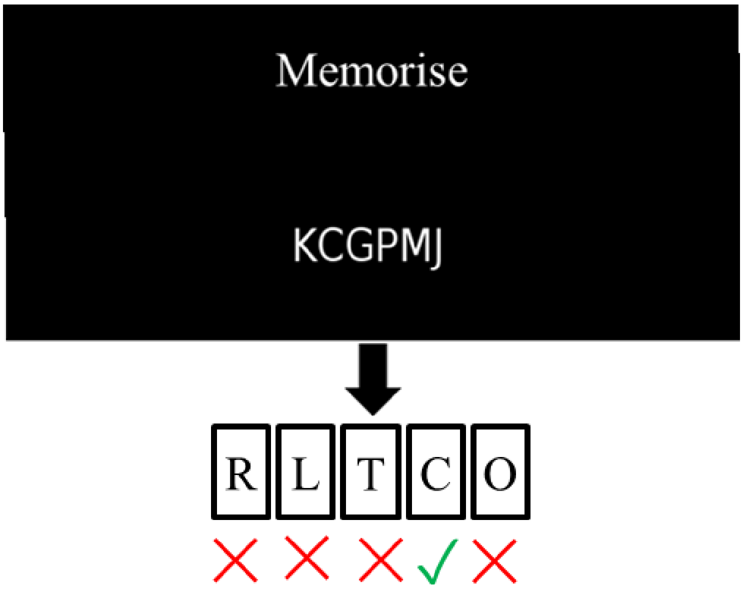


Figure 5-14. Replicate of Sternberg Scanning Test from PEBL test battery (Mueller & Piper, 2014).

The Sternberg scanning test is a memory and identification test (Mueller & Piper, 2014). Participants were required to memorise a sequence of random letters (no time limit). When the participant is ready, the trial starts by flashing a series of random letters, one at a time. For each stimulus, the participant had to respond with 'shift' keys on the keyboard to indicate if the stimuli were present in the memorised sequence (see Figure 5-14). If there was an error made, the original stimulus would be displayed on the screen again to memorise again. The sequence length starts with two letters (easy), increasing to six letters (difficult). Each sequence had 50 trials. The key skills used were working memory and short-term memory (Mueller, 2010).

5.2.2 Analysis

For each PEBL task shown in Table 5-1, the raw data (from the automated output of interest such as reaction time, study time, and success rate) was checked for outliers using the interquartile range (IQR) method. IQR (the median obtained from the difference between 75th and the 25th percentile) defines an outlier if a data point is above the 75th percentile or below the 25th percentile by 1.5 times the IQR. The outliers were removed before analysis. Then, IQR was applied across participants. The data points were tested for its skewness before and after applying IQR. The skewness of the data points could be interpreted as high (less than -1 or greater than 1), moderate (between -1 and -0.5 or between 0.5 and 1), and approximately symmetric (between -0.5 and 0.5) (Singh, 2019). Table 5-2 shows that before removing the outliers, the data points were highly skewed to the right. Upon removing the outliers, the data points range between approximately symmetric and moderately skewed to the right.

Model 0 is the base model built on covariates (Formaldehyde, Carbon monoxide, Bacteria count, and Fungi count), participant ID and week (scaled and centred). Model 1, 2, and 3 each was built on IAQ parameters: $PM_{2.5}$ + Model 0, TVOC + Model 0, and CO_2 + Model 0, respectively. P-values < 0.05 were statistically significant. The details of the hierarchical model structures were described in Chapter 3, section 3.5. The summary of the data points for each task used for analysis is shown in Table 5-1 and the skewness of the data is represented in Table 5-2.

Table 5-1. Summary of the data points after removing outliers for PEBL test battery.

Task	**Data points before removal**	**Outlier**	**Data points after removal**	**Percentage removed**
Matrix Rotation Test	8613	861	7752	10.0
Mental Rotation Test	55322	1270	54052	2.3
Time-Wall Test	10754	324	10430	3.0
Tower of London Test	11248	0	11248	0
Berg's Card Sorting Test	34304	2940	31364	8.6
Switcher Test	4824	204	4620	4.2
Two Column Addition	19558	0	19558	0
Hicks Law Test	157800	10335	147465	6.5
Trail making Test	6389	302	6087	4.7
Victoria Stroop Test	37872	2126	35746	5.6
Continuous Performance Test	178629	22038	156591	12.3

Operation Span	7566	268	7298	3.5
Sternberg Scanning Test	151828	11761	140067	7.7

Table 5-2. Summary of mean, variance, and skewness of the data points before removing the outliers. After removing the outliers using the IQR method, the skewness of the data point is reported.

Task	Mean	Variance	Skewness	Skewness (after removing outliers)
Working Memory				
Operation Span Test	1415.15	309355.6	1.5	0.7
Sternberg Scanning Test	950.657	456123.2	11.7	1.0
Attention				
Continuous Performance Test	352.534	26700.44	2.7	0.5
Switcher Test	1344.47	393455.2	5.5	0.5
Response Inhibition				
Hicks Law Test	393.888	43382.3	7.4	0.2
Victoria Stroop Colour Test	1008.21	699633.3	4.3	0.7
Cognitive Flexibility and Control				
BCST	1121.4	771017.1	9.3	1.0
Time-Wall Test	5.53412	37.24199	22.6	0.8
Trail making Test	13354.2	7639088	2.1	0.5
Speed of Information Processing				
Two-column Addition Test	7754.79	7131330	0.6	0.6
Fluid Intelligence				
Matrix Rotation Test	1614.59	2400223	8.5	1.1
Mental Rotation Test	1236.29	257494.7	0.8	0.5
Planning				
TOL-R Test	15744.3	126987446.00	2.9	0.9

5.3 Results

The results for each task of the cognitive test battery are presented separately with a hierarchical regression table. The best-fitted model selected is highlighted in bold. The graphs show the effect of the main predictor of the selected model. The first graph with all the data points is shown. To make the effect clear, zoomed in to the predicted mean data points with 95% confidence intervals are represented in the second graph.

5.3.1 Working Memory

5.3.1.1 Operation Span Test

The measurement outcome variables comprised time taken to respond (distractor and memory trials) and correct/incorrect entries from the distractor and the letter sequence. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, time, correct entries for memory trials, and interactions as correct or incorrect entries for distractor and memory trials. The best-fitted model involves the time taken for correct entries (both distractor and memory trials) satisfying the Bonferroni adjusted null hypothesis shown in Table 5-3.

Table 5-3. Linear mixed regression model testing the effect of IAQ parameters on time taken for correct entries and treating 90 participants as a random intercept.

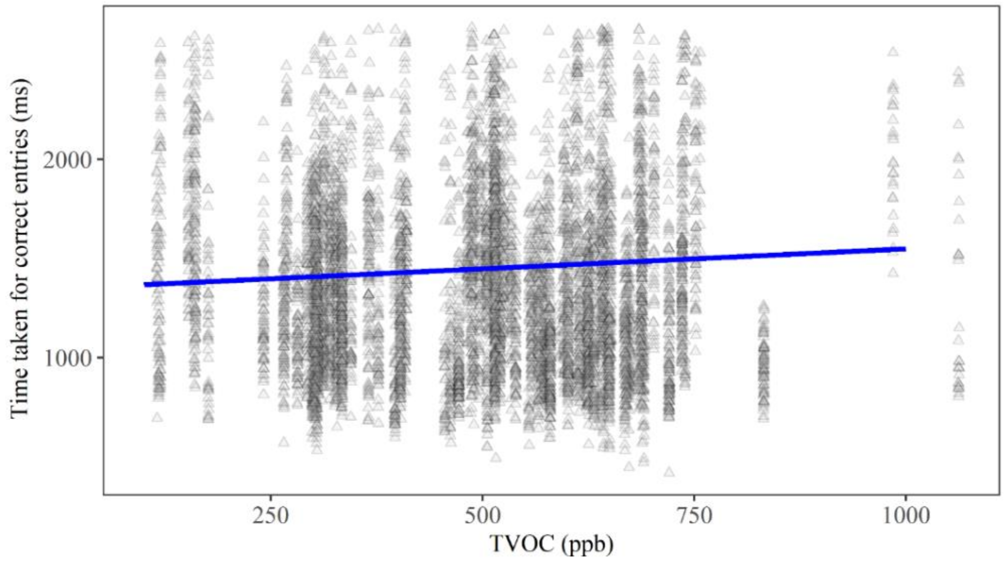
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value*), {effect size}			
	Model 0	Model 1	**Model 2**	Model 3
Scaled Week	-0.24	-0.23	**-0.24**	-0.23
	[-0.26, -0.23]	[-0.25, -0.22	**[-0.25, -0.23]**	[-0.25, -0.22]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.42}	{0.39}	**{0.42}**	{0.38}
Fungi	-0.001	-0.02	**-0.02**	-0.001
	[-0.02, 0.01]	[-0.04, -0.01]	**[-0.03, 0]**	[-0.02, 0.01]
	(0.23)	(0.007*)	**(0.027)**	(0.28)
	{0.01}	{0.03}	**{0.03}**	{0.01}
Bacteria	0.001	0.001	**-0.001**	0.001
	[-0.01, 0.02]	[-0.01, 0.02]	**[-0.02, 0.01]**	[-0.01, 0.02]
	(0.22)	(0.25)	**(0.53)**	(0.55)
	{0.01}	{0.01}	**{0}**	{0}
Formaldehyde	-0.03	-0.03	**-0.03**	-0.03
	[-0.05, -0.01]	[-0.05, -0.01]	**[-0.05, -0.01]**	[-0.05, -0.01]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.04}	{0.04}	**{0.04}**	{0.04}
CO	-0.02	-0.02	**-0.03**	-0.03
	[-0.03, 0]	[-0.03, 0]	**[-0.04, -0.02]**	[-0.04, -0.01]
	(0.01*)	(0.02*)	**(< 0.001*)**	(< 0.001*)
	{0.01}	{0.03}	**{0.05}**	{0.04}
$PM_{2.5}$		0.04		
		[0.02, 0.05]		
		(< 0.001*)		
		{0.06}		
TVOC			**0.07**	
			[0.05, 0.08]	
			(< 0.001*)	

			{0.12}	
CO_2				0.03
				[0.01, 0.05]
				(< 0.001*)
				{0.04}
AIC	101052.9	101023.4	**100962.8**	101057.4
AIC Weightage	0%	0%	**100%**	0%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 2 in Table 5-3 with an AIC value of 100962.8, carrying 100% of the cumulative weight. The Model 2 intercept (fixed variables = 0) is at 1502.23 (95% CI [1400.1,1604.3], $t(7289) = 28.9$, $p < .001$). The predicted values from Model 2 showed a positive effect of TVOC (standardised beta = 0.07, $p < .001$) on time taken for correct entries. It is to be noted that the significance seen among covariates was not considered due to its weak association with the IAQ parameter. The effect size of Model 2 showed a small effect. The linear relationship between the time taken for correct entries and the concentration levels of TVOC is shown in Figure 5-15. As the concentration levels of TVOC increase, more time is taken for correct entries.

A)



B)

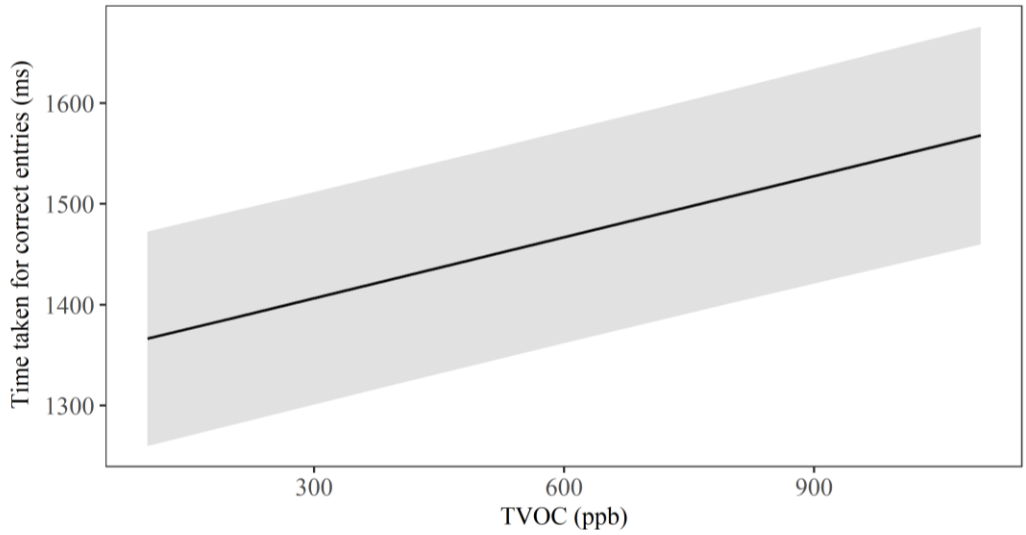


Figure 5-15. Effect of TVOC on the reaction time (ms) in model 2. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.1.2 Sternberg Scanning Test

The measurement outcome variables comprised reaction time, sequence length and correct/incorrect entries. Each of the outcome variables is associated with dependent variables. Separate sets of hierarchical models were analysed based on the dependent variables, reaction time, correct entries, and interactions as sequence length and correct or incorrect entries. The best-fitted model involves the time taken for the correct response to satisfy the Bonferroni adjusted null hypothesis shown in Table 5-4.

Table 5-4. Linear mixed regression model testing the effect of IAQ parameters on reaction time (ms) taken for correct response and treating 90 participants as a random intercept.

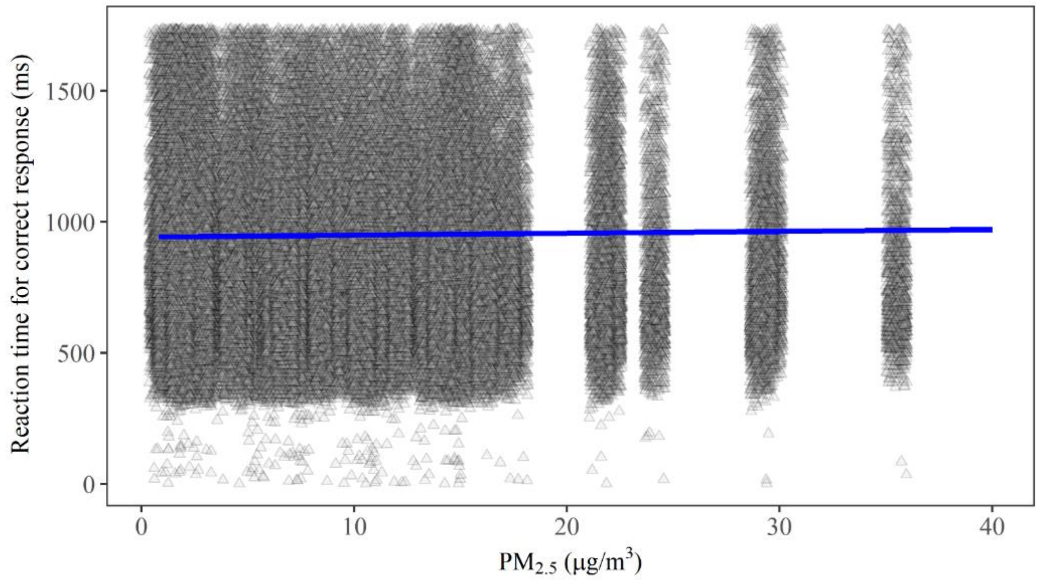
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	**Model 1**	Model 2	Model 3
Scaled Week	-0.06	**-0.06**	-0.06	-0.06
	[-0.06, -0.05]	**[-0.06, -0.05]**	[-0.06, -0.05]	[-0.07, -0.06]
	(< 0.001*)	**(< 0.001*)**	(< 0.001*)	(< 0.001*)
	{0.05}	**{0.05}**	{0.05}	{0.05}
Fungi	0.001	**0.001**	0.001	0.001
	[0, 0.02]	**[0, 0.01]**	[0, 0.02]	[0, 0.01]
	(0.005*)	**(0.06)**	(0.004*)	(0.007*)
	{0}	**{0}**	{0}	{0}
Bacteria	-0.001	**-0.001**	-0.001	-0.001
	[-0.01, 0.02]	**[-0.01, 0.02]**	[-0.02, 0.01]	[-0.01, 0.02]
	(0.03*)	**(0.03*)**	(0.05)	(0.13)
	{0}	**{0}**	{0}	{0}
Formaldehyde	-0.02	**-0.02**	-0.02	-0.02
	[-0.02, -0.01]	**[-0.02, -0.01]**	[-0.02, -0.01]	[-0.02, -0.01]
	(< 0.001*)	**(< 0.001*)**	(< 0.001*)	(< 0.001*)
	{0.01}	**{0.01}**	{0.01}	{0.01}
CO	0.001	**0.001**	0.001	0.001
	[0, 0.01]	**[0, 0.01]**	[0, 0.01]	[0, 0.01]
	(0.09)	**(0.08)**	(0.07)	(0.008*)

	{0}	**{0}**	{0}	{0}
$PM_{2.5}$		**0.001**		
		[0, 0.01]		
		(0.005*)		
		{0}		
TVOC			-0.001	
			[-0.01, 0]	
			(0.42)	
			{0}	
CO_2				-0.01
				[-0.02, 0]
				(0.002*)
				{0}
AIC	2396599.2	**2396594.1**	2396607.8	2396597.0
AIC Weightage	5.8%	**76.8%**	0%	17.4%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 1 in Table 5-4 with an AIC value of 2396594.1, carrying 76.8% of the cumulative weight. The Model 1 intercept (fixed variables = 0) is at 978.2 (95% CI [923.3,1033.0], t (151819) = 34.9, $p < .001$). The predicted values from Model 1 showed a positive effect of $PM_{2.5}$ (standardised beta = $8.1e^{-3}$, p = 0.005) on reaction time for correct response. It is to be noted that the significance seen among covariates was not considered due to its weak association with the IAQ parameter. The effect size of Model 1 showed a small effect. The linear relationship between the reaction time for correct response and the concentration levels of $PM_{2.5}$ is shown in Figure 5-16. As the concentration levels of $PM_{2.5}$ increase, more time is taken to attain the correct response.

A)



B)

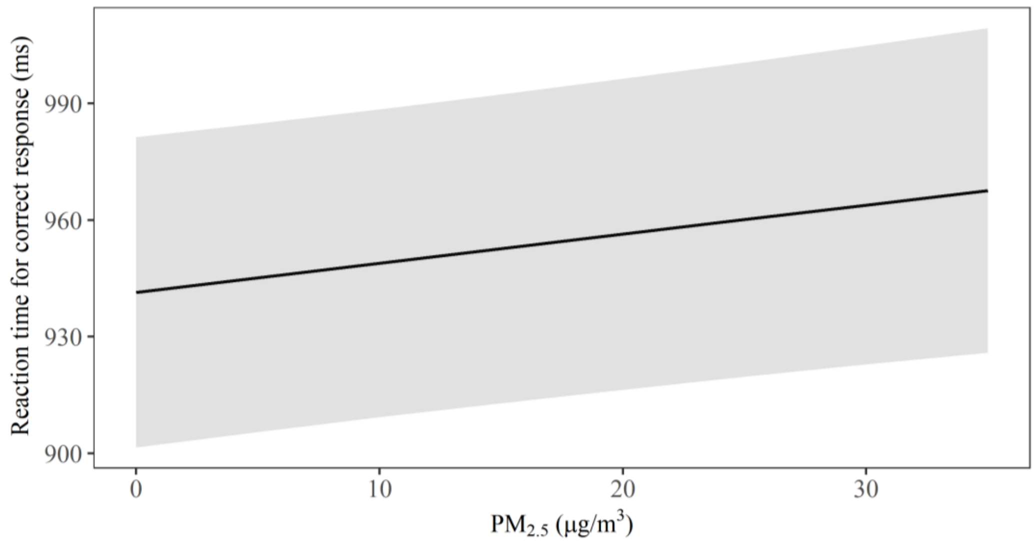


Figure 5-16. Effect of $PM_{2.5}$ on the reaction time (ms) in model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.2 Attention

5.3.2.1 Continuous Performance Test

The measurement outcome variables comprised reaction time and correct/incorrect entries. Each of the outcome variables is associated with dependent variables. Separate sets of hierarchical models were analysed based on the dependent variables, reaction time, correct entries, and interactions as correct or incorrect entries. The best-fitted model involves the reaction time to respond to the correct stimuli and satisfies the Bonferroni adjusted null hypothesis shown in Table 5-5.

Table 5-5. Linear mixed regression model testing the effect of IAQ parameters on reaction time (ms) for correct responses and treating 90 participants as a random intercept.

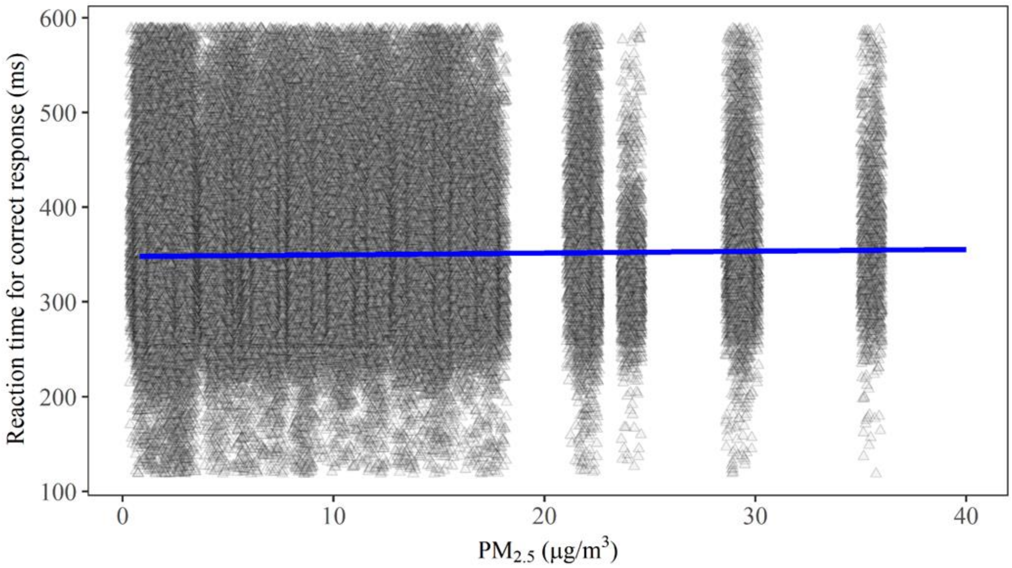
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	**Model 1**	Model 2	Model 3
Scaled Week	-0.001	**-0.001**	-0.001	-0.001
	[-0.01, 0]	**[-0.01, 0]**	[-0.01, 0]	[-0.01, 0]
	(0.22)	**(0.74)**	(0.22)	(0.23)
	{0}	**{0}**	{0}	{0}
Fungi	0.001	**-0.001**	0.001	0.001
	[0, 0.01]	**[-0.01, 0.01]**	[-0.01, 0.02]	[-0.01, 0.02]
	(0.42)	**(0.85)**	(0.42)	(0.43)
	{0}	**{0}**	{0}	{0}
Bacteria	-0.001	**-0.001**	-0.001	-0.001
	[-0.01, 0]	**[-0.01, 0]**	[-0.01, 0]	[-0.01, 0]
	(0.43)	**(0.4)**	(0.45)	(0.46)
	{0}	**{0}**	{0}	{0}
Formaldehyde	0.001	**0.001**	0.001	0.001
	[0, 0.01]	**[0, 0.01]**	[0, 0.01]	[0, 0.01]
	(0.7)	**(0.69)**	(0.69)	(0.7)
	{0}	**{0}**	{0}	{0}
CO	-0.001	**-0.001**	-0.001	-0.001

	[-0.01, 0]	**[-0.01, 0]**	[-0.01, 0]	[-0.01, 0]
	(0.19)	**(0.21)**	(0.21)	(0.25)
	{0}	**{0}**	{0}	{0}
$PM_{2.5}$		**0.01**		
		[0.01, 0.02]		
		(< 0.001*)		
		{0.01}		
TVOC			-0.001	
			[-0.01, 0]	
			(0.93)	
			{0}	
CO_2				-0.001
				[-0.01, 0.01]
				(0.84)
				{0}
AIC	1790532.4	**1790519.9**	1790534.2	1790542.3
AIC Weightage	0.2%	**99.7%**	0.1%	0%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 1 in Table 5-5 with an AIC value of 2317662.9, carrying 88.0% of the cumulative weight. The Model 1 intercept (fixed variables = 0) is at 365.1 (95% CI [357.3 372.8], $t(156582) = 92.4$, $p < .001$). The predicted values from Model 1 showed a positive effect of $PM_{2.5}$ (standardised beta = 0.01, $p < .001$) on reaction time for correct responses. The effect size of Model 1 showed a small effect. The linear relationship between the reaction time for correct responses and the concentration levels of $PM_{2.5}$ is shown in Figure 5-17. As the concentration levels of $PM_{2.5}$ increase, more time is taken for the correct response.

A)



B)

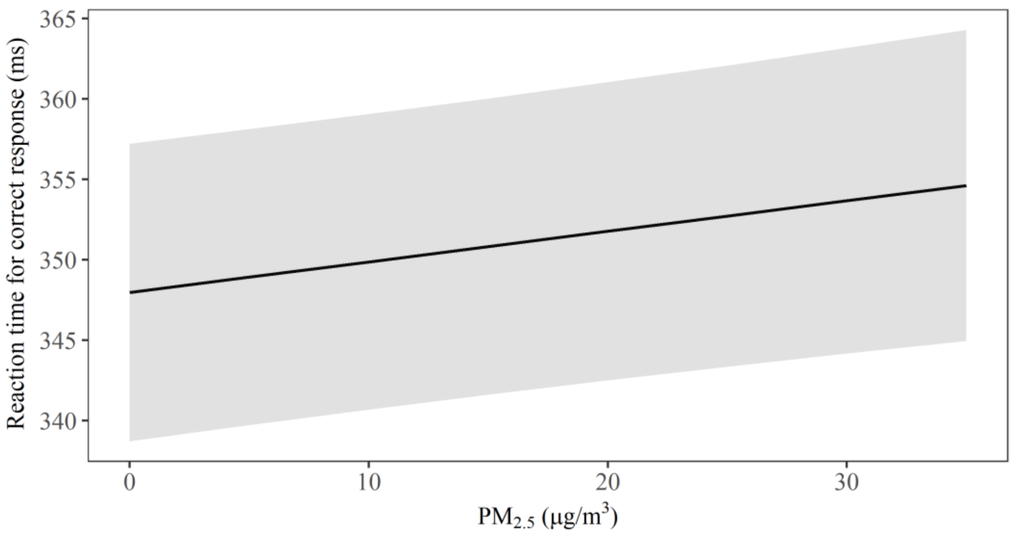


Figure 5-17. Effect of $PM_{2.5}$ on the reaction time (ms) in Model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.2.2 Switcher Test

The measurement outcome variables comprised the time taken to study the stimuli before the first move, time taken to complete the trial, and response accuracy. The accuracy was determined by dividing the number of errors made over 12 stimuli. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, accuracy, total time taken to complete the test, time taken to study before the first move, and interactions of test type. The best-fitted model involves time taken to study before making their first move (study time) satisfies the Bonferroni adjusted null hypothesis shown in Table 5-6.

Table 5-6. Linear mixed regression model testing the effect of IAQ parameters on study time and treating 90 participants as a random intercept.

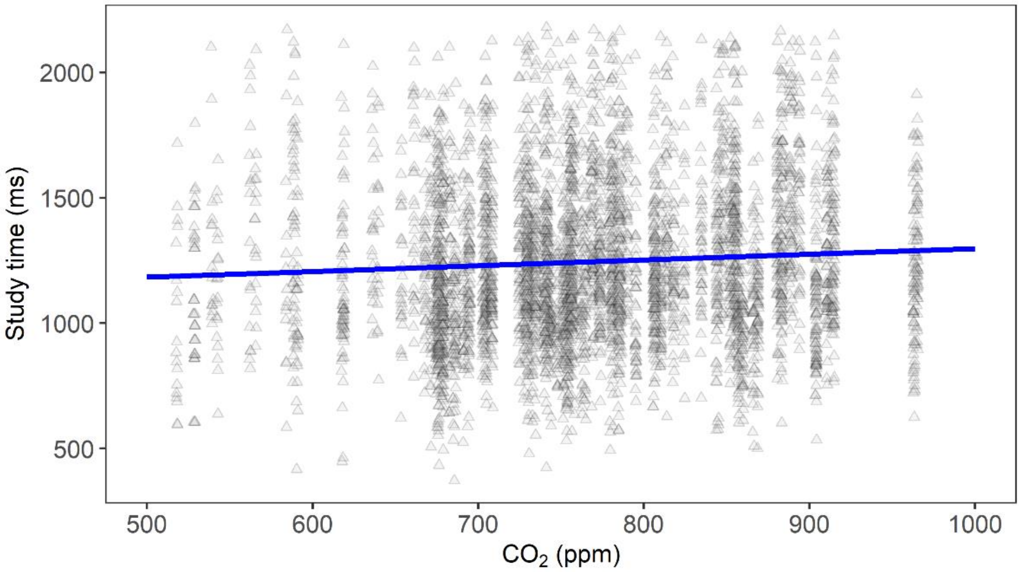
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	Model 1	Model 2	**Model 3**
Scaled Week	-0.25	-0.24	-0.24	**-0.3**
	[-0.27, -0.22]	[-0.27, -0.21]	[-0.27, -0.22]	**[-0.33, -0.27]**
	(< 0.001*)	(< 0.001*)	(< 0.001*)	**(< 0.001*)**
	{0.25}	{0.24}	{0.25}	**{0.31}**
Fungi	0	0	0	**0**
	[-0.03, 0.03]	[-0.04, 0.02]	[-0.04, 0.02]	**[-0.03, 0.03]**
	(0.88))	(0.55)	(0.54)	**(0.86)**
	{0}	{0}	{0}	**{0}**
Bacteria	0	0	-0.02	**-0.02**
	[-0.03, 0.03]	[-0.04, 0.03]	[-0.05, 0.02]	**[-0.05, 0.01]**
	(0.79)	(0.79)	(0.32)	**(0.3)**
	{0}	{0}	{0.01}	**{0.02}**
Formaldehyde	0.02	-0.02	0.02	**-0.01**
	[-0.01, 0.05]	[-0.01, 0.05]	[-0.01, 0.05]	**[-0.04, 0.05]**
	(0.25)	(0.24)	(0.27)	**(0.52)**
	{0.02}	{0.02}	{0.02}	**{0}**
CO	0.01	0.02	0	**-0.02**

	[-0.01, 0.04]	[-0.01, 0.04]	[-0.03, 0.03]	**[-0.05, 0.01]**
	(0.32)	(0.31)	(0.78)	**(0.23)**
	{0.01}	{0.01}	{0}	**{0.02}**
$PM_{2.5}$		0.02		
		[0, 0.05]		
		(0.13)		
		{0.02}		
TVOC			0.05	
			[0.03, 0.08]	
			(< 0.001*)	
			{0.06}	
CO_2				**0.06**
				[0.03, 0.1]
				(< 0.001*)
				{0.05}
AIC	64041.0	64042.0	64035.8	**64035.3**
AIC Weightage	3.1%	1.8%	42.5%	**52.5%**

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 3 in Table 5-6 with an AIC value of 64035.3, carrying 52.5% of the cumulative weight. The Model 3 intercept (fixed variables = 0) is at 1139.4 (95% CI [1016.7, 1262.1], t (4544) = 18.2, $p < .001$). The predicted values from Model 3 showed a positive effect of CO_2 (standardised beta = 0.06, $p< .001$) on the study time. The effect size of Model 3 showed a small effect. The linear relationship between the study time and the concentration levels of CO_2 is shown in Figure 5-18. As the concentration of CO_2 increases, the longer it takes to remember all the rule sequences.

A)



B)

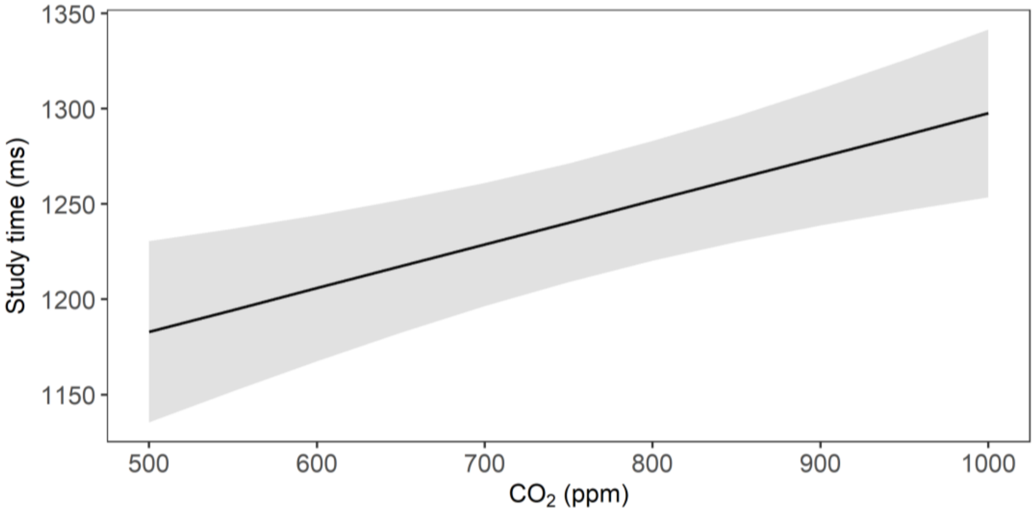


Figure 5-18. Effect of CO_2 on the reaction time (ms) in model 3. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.3 Response Inhibition

5.3.3.1 Hicks Law Test

The measurement outcome variables comprised participants' reaction time and correct/incorrect entries. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, reaction time, 8 variations, correct entries, and interactions of variations. The best-fitted model involves the reaction time taken for correct responses and satisfies the Bonferroni adjusted null hypothesis shown in Table 5-7.

Table 5-7. Linear mixed regression model testing the effect of IAQ parameters on reaction time (ms) for correct responses and treating 90 participants as a random intercept.

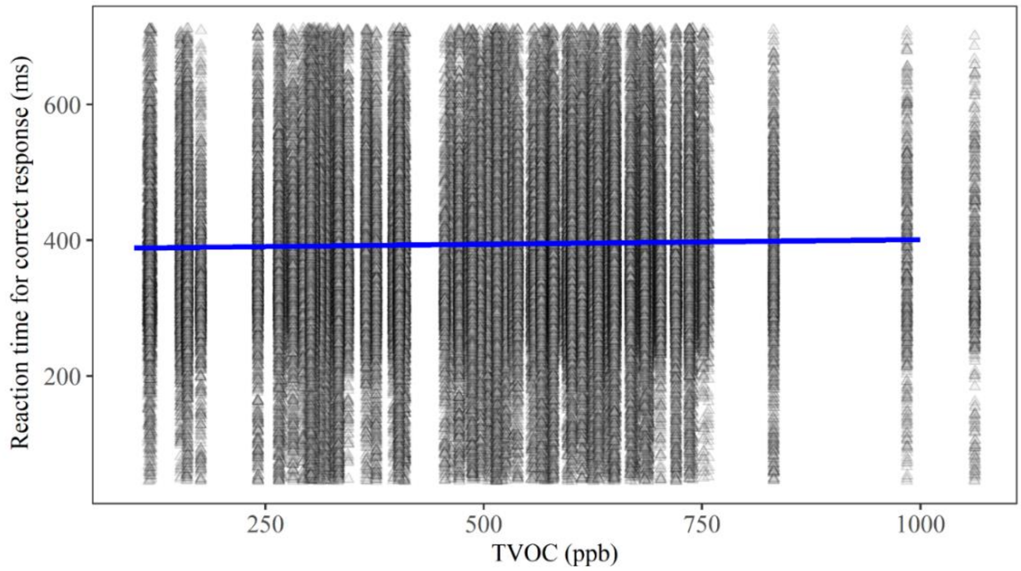
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	Model 1	**Model 2**	Model 3
Scaled Week	-0.06	-0.08	**-0.05**	-0.09
	[-0.06, -0.05]	[-0.09, -0.07]	**[-0.05, -0.04]**	[-0.1, -0.07]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.05}	{0.05}	**{0.05}**	{0.05}
Fungi	0.001	-0.01	**-0.001**	-0.001
	[0, 0.01]	[-0.01, 0.01]	**[-0.01, 0.01]**	[0, 0.01]
	(0.29)	(0.71)	**(0.57)**	(0.24)
	{0}	{0.01}	**{0}**	{0}
Bacteria	0.001	-0.001	**-0.001**	-0.001
	[-0.01, 0.01]	[-0.01, 0.01]	**[-0.01, 0]**	[-0.01, 0.01]
	(0.84)	(0.87)	**(0.62)**	(0.74)
	{0}	{0}	**{0}**	{0}
Formaldehyde	0.001	-0.001	**-0.001**	-0.001
	[0, 0.02]	[0, 0.02]	**[0, 0.01]**	[0, 0.02]
	(0.01*)	(0.01*)	**(0.03)**	(0.01*)
	{0}	{0}	**{0}**	{0}
CO	0.001	-0.001	**-0.001**	-0.001

	[0, 0.01]	[0, 0.01]	**[0, 0.01]**	[0, 0.01]
	(0.02*)	(0.02*)	**(0.14)**	(0.35)
	{0}	{0}	**{0}**	{0}
$PM_{2.5}$		0.001		
		[0, 0.01]		
		(0.002*)		
		{0}		
TVOC			**0.01**	
			[0.01, 0.02]	
			(< 0.001*)	
			{0.01}	
CO_2				0.01
				[-0, 0.02]
				(0.001*)
				{0}
AIC	1757409.1	1757414.7	**1757403.0**	**1757409.4**
AIC Weightage	4.2%	0.3%	**91.8%**	3.7%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 2 in Table 5-7 with an AIC value of 2033427.9, carrying 85.0% of the cumulative weight. The Model 2 intercept (fixed variables = 0) is at 357.0 (95% CI [347.6, 366.4], t (141254) = 74.5, p < .001). The predicted values from Model 2 showed a positive effect of TVOC (standardised beta = 0.01, p< .001) on reaction time for correct response. The effect size of Model 2 showed a small effect. The linear relationship between the reaction time for correct response and the concentration levels of TVOC is shown in Figure 5-19. As the concentration levels of TVOC increase, more time is taken to respond to the stimuli.

A)



B)

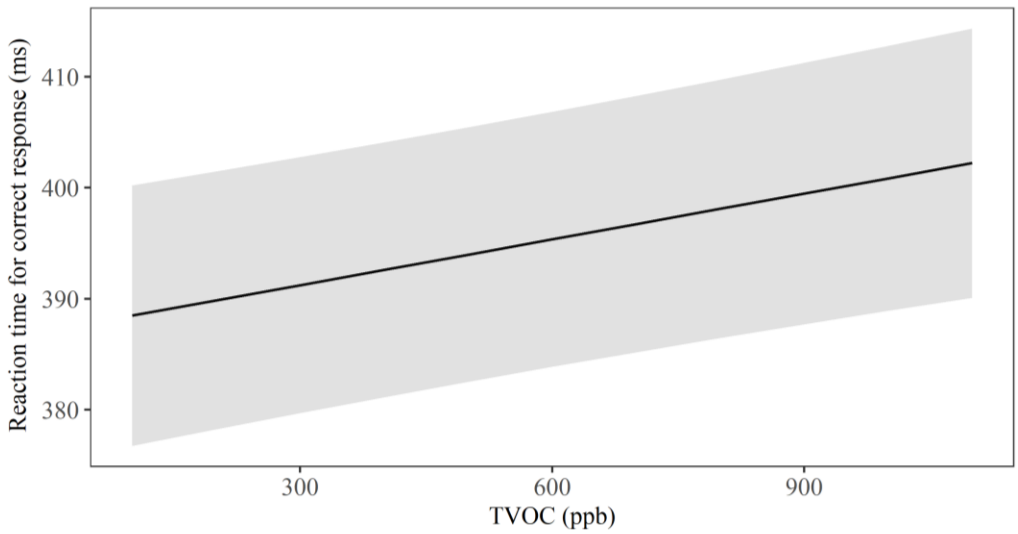


Figure 5-19. Effect of TVOC on the reaction time (ms) in model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.3.2 Victoria Stroop Colour Test

The measurement outcome variables comprised reaction time blocks 1, 2, and 3 and correct/incorrect entries. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, reaction time, correct entries, and interactions as a block. Individual analysis of the blocks revealed that block 3 (coloured words) is not statistically significant. Hence, they are not included in the separate sets of hierarchical models for test analysis. The best-fitted model involves reaction time taken for correct responses gathered for blocks 1 and 2 satisfies the null hypothesis (showed statistical significance, adjusted p-value <0.0125 in $PM_{2.5}$, TVOC or CO_2) was chosen for presentation in Table 5-8.

Table 5-8. Linear mixed regression model testing the effect of IAQ parameters on reaction time (ms) for correct responses and treating 90 participants as a random intercept.

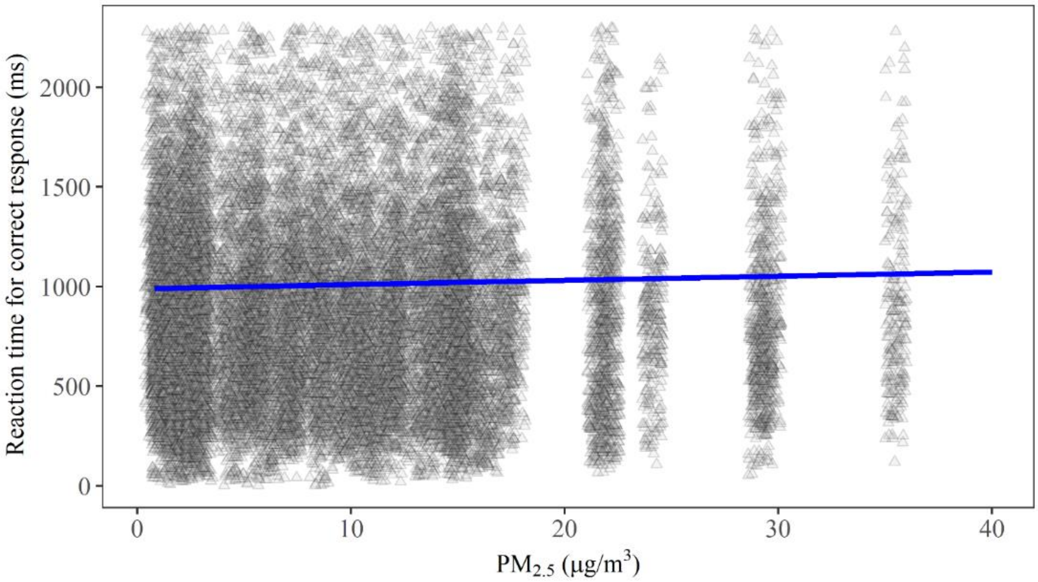
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	**Model 1**	Model 2	Model 3
Scaled Week	-0.11	**-0.10**	-0.11	-0.10
	[-0.12, -0.10]	**[-0.12, -0.09]**	[-0.12, -0.10]	[-0.12, -0.09]
	(< 0.001*)	**(< 0.001*)**	(< 0.001*)	(< 0.001*)
	{0.1}	**{0.09}**	{0.1}	{0.09}
Fungi	0.001	**-0.001**	0.001	0.001
	[-0.01, 0.02]	**[-0.02, 0.02]**	[-0.01, 0.02]	[-0.01, 0.02]
	(0.45)	**(0.93)**	(0.61)	(0.42)
	{0}	**{0}**	{0}	{0}
Bacteria	-0.001	**-0.001**	-0.001	-0.001
	[-0.02, 0.01]	**[-0.02, 0.01]**	[-0.02, 0.01]	[-0.02, 0.01]
	(0.63)	**(0.6)**	(0.41)	(0.37)
	{0}	**{0}**	{0}	{0}
Formaldehyde	-0.001	**-0.001**	-0.001	-0.001
	[-0.02,0.01]	**[-0.02, 0.01]**	[-0.02, 0.01]	[-0.02, 0.01]
	(0.76)	**(0.77)**	(0.72)	(0.82)

	{0}	**{0}**	{0}	{0}
CO	-0.001	**-0.001**	-0.001	-0.001
	[-0.02, 0.01]	**[-0.02, 0.01]**	[-0.02, 0.01]	[-0.02, 0.01]
	(0.78)	**(0.82)**	(0.52)	(0.24)
	{0}	**{0}**	{0}	{0}
$PM_{2.5}$		**0.03**		
		[0.02, 0.05]		
		(< 0.001*)		
		{0.03}		
TVOC			0.01	
			[0, 0.03]	
			(0.03*)	
			{0.01}	
CO_2				0.02
				[0.01, 0.04]
				(0.01*)
				{0.02}
AIC	358152.2	**358132.8**	358153.9	358158.2
AIC Weightage	0%	**100%**	0%	0%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 1 in Table 5-8 with an AIC value of 358132.8, carrying 100% of the cumulative weight. The Model 1 intercept (fixed variables = 0) is at 892.2 (95% CI [818.0, 966.4], $t(23813) = 23.6$, $p < .001$). The predicted values from Model 1 showed a positive effect of $PM_{2.5}$ (standardised beta = 0.03, $p < .001$) on reaction time for correct responses. The effect size of Model 1 showed a small effect. The linear relationship between the reaction time for correct responses and the concentration levels of $PM_{2.5}$ is shown in Figure 5-20. As the concentration levels of $PM_{2.5}$ increase, more time is taken for correct responses.

A)



B)

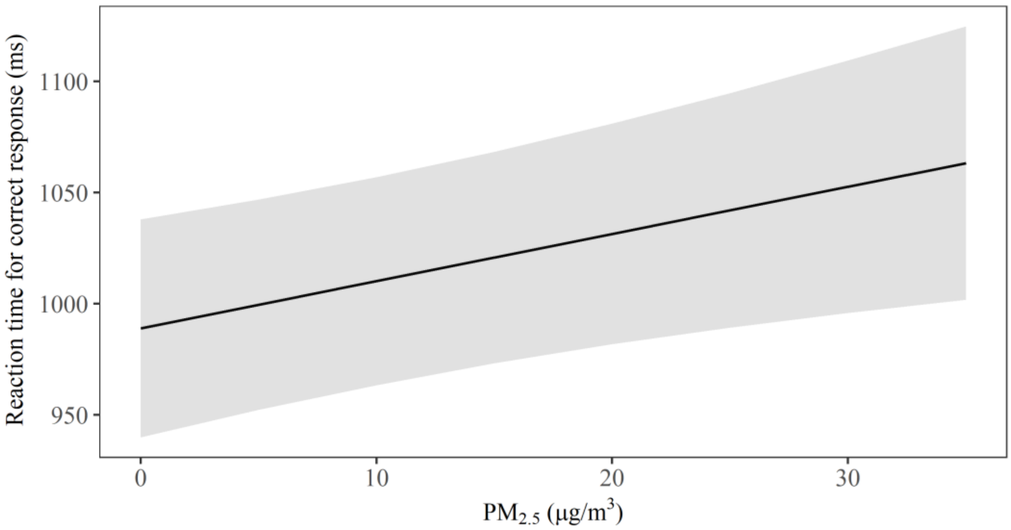


Figure 5-20. Effect of $PM_{2.5}$ on the reaction time (ms) in model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.4 Cognitive Flexibility and Control

5.3.4.1 BCST

The measurement outcome variables comprised the number of correct or incorrect responses, reaction time, and perseveration on the prior rule. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, correct or incorrect response, perseveration error, reaction time, and interactions of perseveration error or correct/incorrect response. The final analysis involved reaction time against the independent variables. As a result, the best-fitted model involves reaction time and satisfies the Bonferroni adjusted null hypothesis shown in Table 5-9.

Table 5-9. Linear mixed regression model testing the effect of IAQ parameters on reaction time (ms) and treating 90 participants as a random intercept.

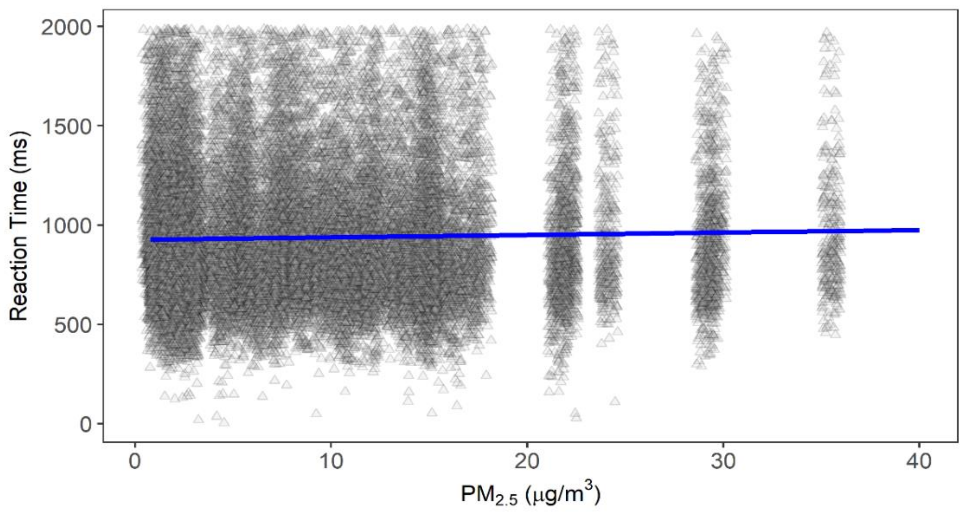
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	**Model 1**	Model 2	Model 3
Scaled Week	-0.15	**-0.15**	-0.15	-0.14
	[-0.17, -0.14]	**[-0.16, -0.14]**	[-0.16, -0.14]	[-0.15, -0.13]
	(< 0.001*)	**(< 0.001*)**	(< 0.001*)	(< 0.001*)
	{0.14}	**{0.14}**	{0.14}	{0.13}
Fungi	0.001	**-0.0001**	0.001	0.001
	[-0.01, 0.02]	**[-0.02, 0.01]**	[-0.01, 0.01]	[-0.01, 0.02]
	(0.34)	**(0.25)**	(0.77)	(0.3)
	{0}	**{0}**	{0}	{0}
Bacteria	0.01	**-0.0001**	0.001	0.001
	[0, 0.02]	**[-0.02, 0.01]**	[-0.01, 0.02]	[0, 0.02]
	(0.06)	**(0.31)**	(0.43)	(0.22)
	{0.01}	**{0}**	{0}	{0}
Formaldehyde	0.01	**0.01**	0.01	0.01
	[0, 0.03]	**[0, 0.03]**	[0, 0.03]	[0, 0.03]
	(0.04*)	**(0.07)**	(0.05)	(0.04*)
	{0.01}	**{0.01}**	{0.01}	{0.01}
CO	0.01	**0.01**	0.001	0.01
	[0, 0.03]	**[0, 0.03]**	[0, 0.02]	[-0.01, 0.02]
	(0.01*)	**(0.02)**	(0.19)	(0.29)
	{0.01}	**{0.01}**	{0}	{0}
$PM_{2.5}$		**0.03**		
		[0.01, 0.04]		
		(< 0.001*)		
		{0.02}		
TVOC			0.03	
			[0.02, 0.04]	
			(< 0.001*)	
			{0.03}	

CO_2				0.03
				[0.01, 0.04]
				(0.002*)
				{0.02}
AIC	450338.3	**450321.7**	450328.4	450341.7
AIC Weightage	0%	**96.5%**	3.5%	0 %

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 1 in Table 5-9 with an AIC value of 450321.7, carrying 96.5% of the cumulative weight. The Model 1 intercept (fixed variables = 0) is at 878.7 (95% CI [831.3, 926.1], t (31355) = 36.3, $p < .001$). The predicted values from Model 1 showed a positive effect of $PM_{2.5}$ (standardised beta = 0.03, $p < .001$) on reaction time. The effect size of Model 1 showed a small effect. The linear relationship between the time taken reaction time and the concentration levels of $PM_{2.5}$ is shown in Figure 5-21. As the concentration level of $PM_{2.5}$ increases, more time is taken to recognise the rule.

A)



B)

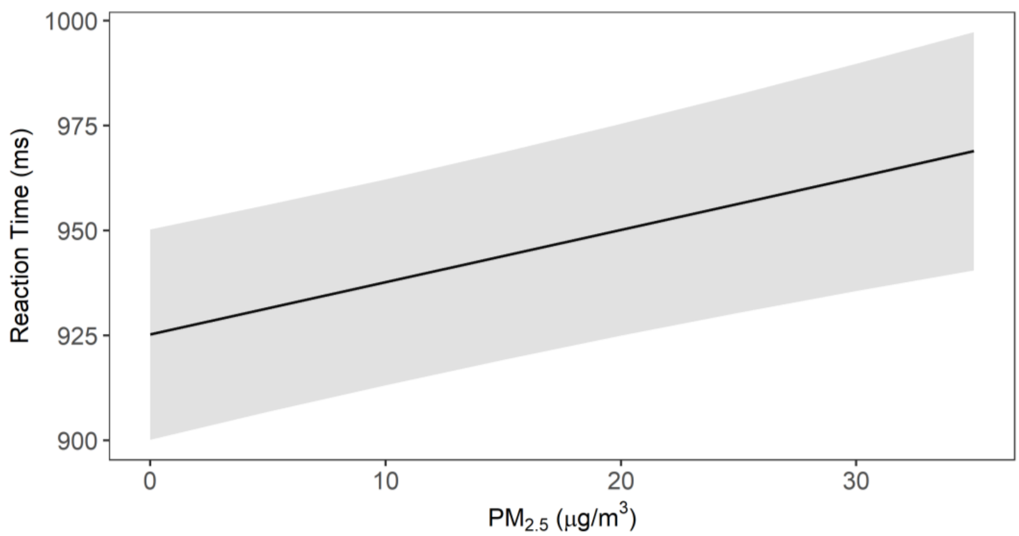


Figure 5-21. Effect of $PM_{2.5}$ on the reaction time (ms) in Model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.4.2 Time-Wall Test

The measurement outcome variables comprised too slow and too fast responses. The possible responses are dummy coded as 1 (too slow) and -1 (too fast). Separate sets of hierarchical models were analysed based on response type (1) as a separate effect and (2) as an interaction. The final analysis involved the accuracy of recognising the pattern expressed in terms of interactions against the independent variables. The best-fitted model examining the accuracy of response and interacting with the response type satisfies the Bonferroni adjusted null hypothesis shown in Table 5-10.

Table 5-10. Linear mixed regression model testing the effect of IAQ parameters on accuracy to predict the pattern and treating 90 participants as a random intercept.

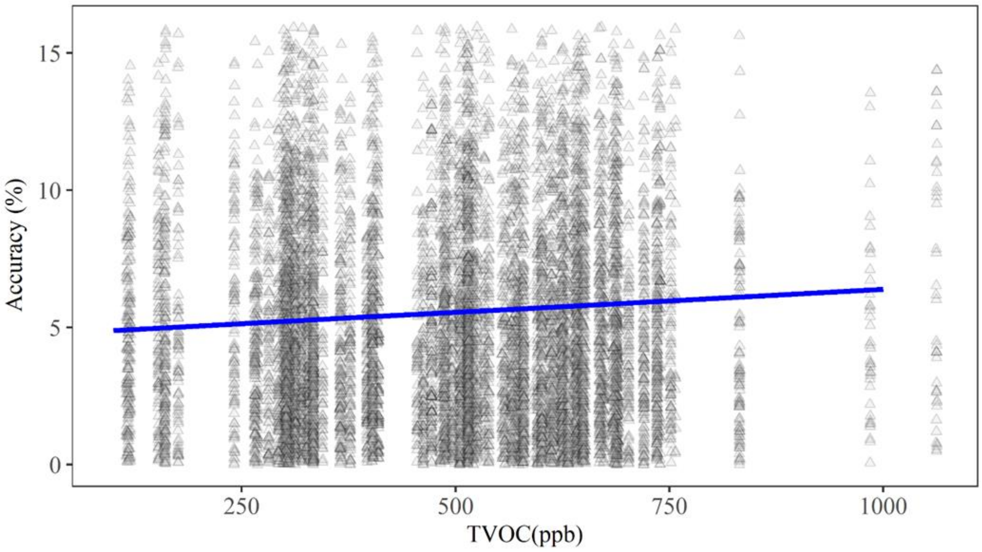
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	Model 1	**Model 2**	Model 3
Scaled Week	-0.05	-0.05	**-0.05**	-0.05
	[-0.07, -0.03]	[-0.07, -0.03]	**[-0.07, -0.03]**	[-0.07, -0.03]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.05}	{0.04}	**{0.05}**	{0.05}
Fungi	0.01	0	**0**	0.01
	[-0.01, 0.04]	[-0.02, 0.03]	**[-0.02, 0.03]**	[-0.01, 0.04]
	(0.36)	(0.8)	**(0.62)**	(0.28)
	{0.01}	{0}	**{0}**	{0.01}
Bacteria	-0.02	-0.02	**-0.03**	-0.02
	[-0.04, 0.01]	[-0.04, 0.01]	**[-0.05, 0]**	[-0.04, 0.01]
	(0.16)	(0.18)	**(0.02)**	(0.13)
	{0.02}	{0.01}	**{0.02}**	{0.02}
Formaldehyde	0	0	**0**	0
	[-0.02, 0.03]	[-0.02, 0.03]	**[-0.02, 0.03]**	[-0.02, 0.03]
	(0.71)	(0.64)	**(0.75)**	(0.67)
	{0}	{0}	**{0}**	{0}
CO	0.01	0.01	**0**	0.03
	[-0.01, 0.03]	[-0.01, 0.03]	**[-0.02, 0.03]**	[-0.01, 0.03]
	(0.21)	(0.19)	**(0.68)**	(0.35)
	{0.01}	{0.01}	**{0.02}**	{0}
Response type		0.04	**-0.08**	0.12
		[-0.02, 0.1]	**[-0.2, 0.04]**	[-0.21, 0.45]
		(< 0.001*)	**(< 0.001*)**	(< 0.001*)
		{0.01}	**{0.01}**	{0}
$PM_{2.5}$		0.02		
		[-0.01, 0.04]		
		(0.18)		
		{0.04}		

$PM_{2.5}$ x response type		0		
		[0, 0.01]		
		(0.15)		
		{0.01}		
TVOC			**0.03**	
			[0, 0.05]	
			(0.03)	
			{0.05}	
TVOC x response type			**0**	
			[0, 0]	
			(0.005*)	
			{0.03}	
CO_2				0.01
				[-0.02, 0.04]
				(0.44)
				{0.10}
CO_2 x response type				0
				[0, 0]
				(0.78)
				{0}
AIC	69044.9	69043.4	**69035.9**	69061.5
AIC Weightage	1.1%	2.2%	**96.7%**	0%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 2 in Table 5-10 with an AIC value of 69035.9, carrying 96.7% of the cumulative weight. The Model 2 intercept (fixed variables = 0) is at 4.83 (95% CI [3.45, 6.21], t (10743) = 6.86, $p < .001$). The predicted values from Model 2 showed a significant positive effect of TVOC (standardised beta = 0.03, $p < 0.05$) on accuracy in predicting the pattern. The effect size of Model 2 showed a small effect. The linear relationship between accuracy (expressed in percentage) in predicting the speed and the concentration levels of TVOC is shown in Figure 5-22. As the concentration levels of TVOC increase, the response accuracy worsens (where 0 is considered perfect accuracy and higher values are considered worse). That is, slow responses become slower and fast responses become faster. The most accurate responses were observed at low TVOC trending to scale 0. The significant interaction between TVOC and response type is plotted in Figure 5-22(B), indicating a steeper slope for too slow responses, i.e., participants were less accurate when they responded late rather than early.

A)



B)

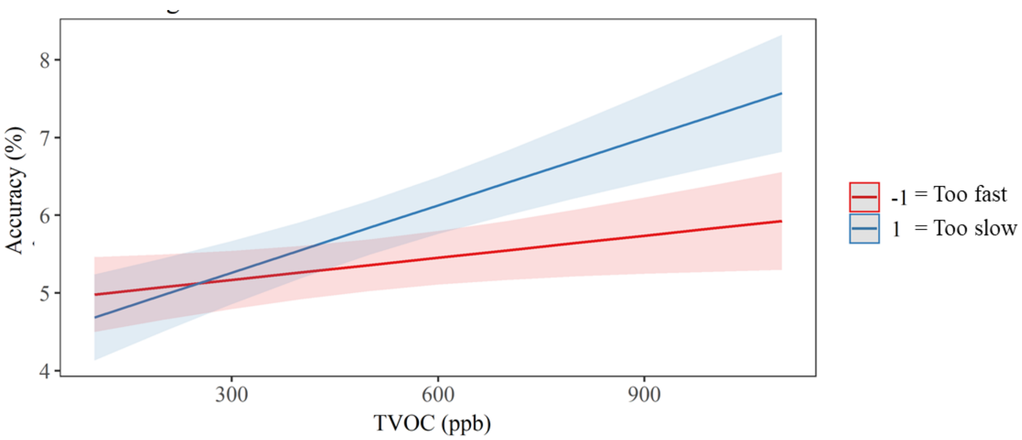


Figure 5-22. Effect of TVOC and percentage of accuracy in model 2. A) Linear mixed regression line with the data points. B) Linear mixed regression lines without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.4.3 Trail making Test

The measurement outcome variables comprised study time (first click), time to complete the trial, and accuracy in clicking on the correct target. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, study time, time to complete, and interactions of type. The best-fitted model involves the study time (Table 5-11) and time taken to complete (Table 5-12) to satisfy the Bonferroni adjusted null hypothesis.

Table 5-11. Linear mixed regression model testing the effect of IAQ parameters on study time and treating 90 participants as a random intercept.

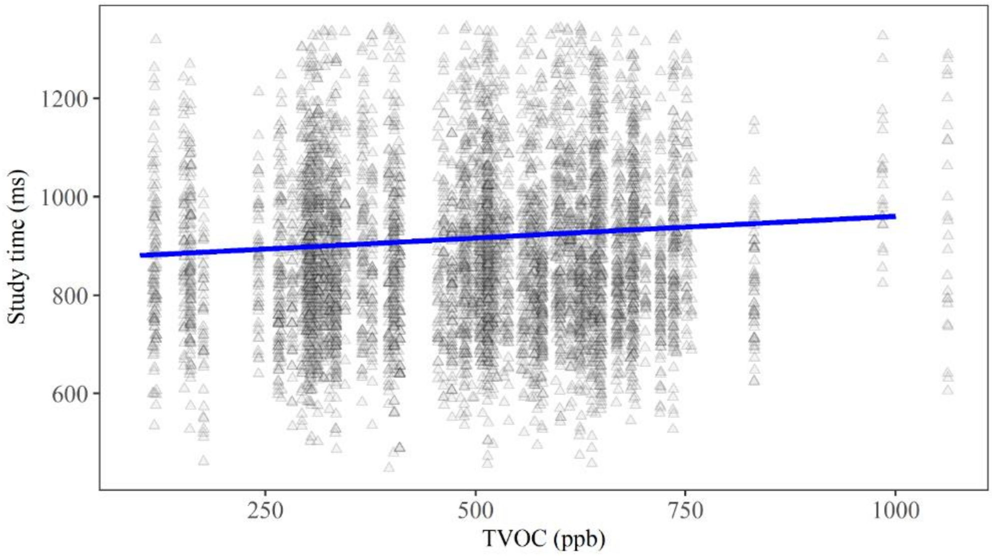
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	Model 1	**Model 2**	Model 3
Scaled Week	-0.19	-0.19	**-0.19**	-0.19
	[-0.22, -0.17]	[-0.21, -0.16]	**[-0.21, -0.16]**	[-0.21, -0.16]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.19}	{0.18}	**{0.19}**	{0.17}
Fungi	0.01	0.001	**0.001**	-0.01
	[-0.01, 0.04]	[-0.02, 0.04]	**[-0.02, 0.04]**	[-0.01, 0.04]
	(0.33)	(0.68)	**(0.63)**	(0.31)
	{0.01}	{0}	**{0}**	{0.01}
Bacteria	0.001	-0.001	**-0.001**	-0.001
	[-0.02, 0.03]	[-0.02, 0.03]	**[-0.04, 0.02]**	[-0.03, 0.03]
	(0.69)	(0.69)	**(0.64)**	(0.98)
	{0}	{0}	**{0}**	{0}
Formaldehyde	-0.01	-0.01	**-0.02**	-0.01
	[-0.04, 0.02]	[-0.04, 0.02]	**[-0.05, 0.01]**	[-0.04, 0.02]
	(0.35)	(0.36)	**(0.3)**	(0.37)
	{0.01}	{0.01}	**{0.01}**	{0.01}
CO	0.03	0.03	**0.02**	0.02
	[0.01, 0.06]	[0.01, 0.06]	**[-0.01, 0.05]**	[-0.01, 0.05]
	(0.01*)	(0.01*)	**(0.11)**	(0.14)
	{0.03}	{0.03}	**{0.02}**	{0.02}

$PM_{2.5}$		0.02		
		[0, 0.05]		
		(0.08)		
		{0.02}		
TVOC			**0.05**	
			[0.03, 0.08]	
			(< 0.001*)	
			{0.05}	
CO_2				0.04
				[0, 0.07]
				(0.04*)
				{0.03}
AIC	84997.3	84996.1	**84987.4**	85000.2
AIC Weightage	0.7%	1.3%	**97.8%**	0.2%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 2 in Table 5-11 with an AIC value of 88901.8, carrying 99.0% of the cumulative weight. The Model 2 intercept (fixed variables = 0) is at 872.5 (95% CI [797.8, 947.3], t (6103) = 22.9, $p < .001$). The predicted values from Model 2 showed a positive effect of TVOC (standardised beta = 0.05, $p < .001$) on study time. The effect size of Model 2 showed a small effect. The linear relationship between the study time and the concentration levels of TVOC is shown in Figure 5-23. As the concentration levels of TVOC increase, more time is taken to study the trial.

A)



B)

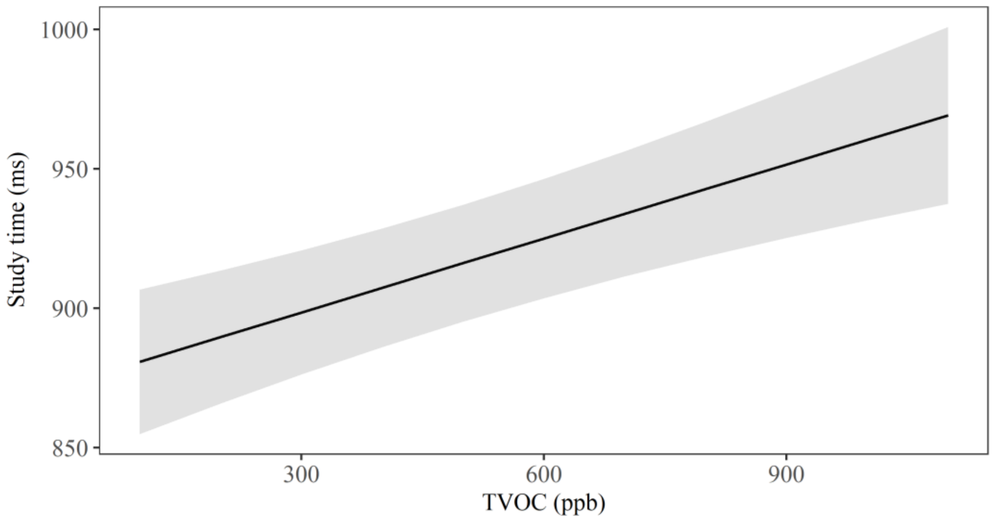


Figure 5-23. Effect of TVOC on the reaction time (ms) in model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

Table 5-12. Linear mixed regression model testing the effect of IAQ parameters on time taken to complete and treating 90 participants as a random intercept.

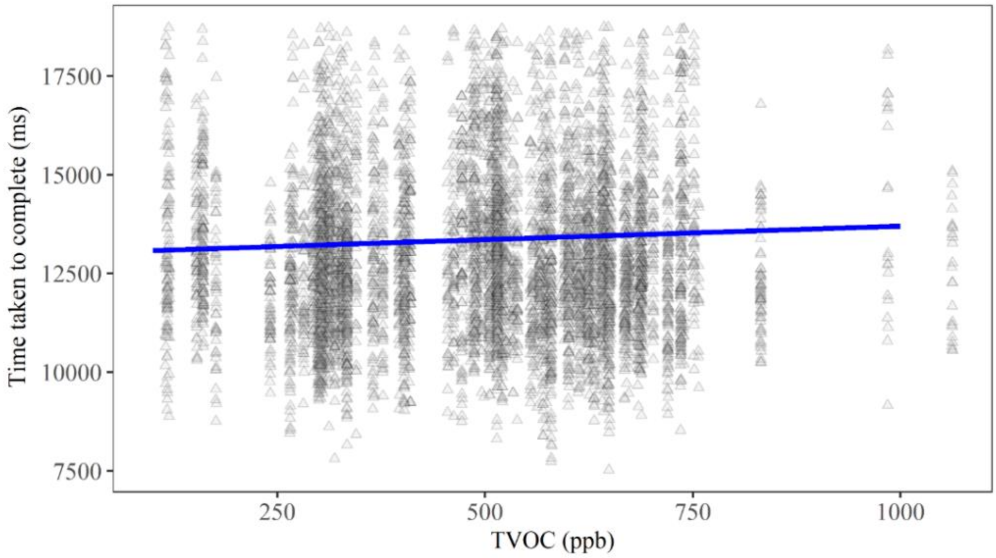
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	Model 1	**Model 2**	Model 3
Scaled Week	-0.14	-0.14	**-0.14**	-0.13
	[-0.17, -0.12]	[-0.16, -0.12]	**[-0.16, -0.12]**	[-0.15, -0.11]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.17}	{0.16}	**{0.16}**	{0.14}
Fungi	0.001	0.001	**0.001**	0.001
	[-0.02, 0.03]	[-0.02, 0.03]	**[-0.02, 0.03]**	[-0.02, 0.03]
	(0.56)	(0.69)	**(0.89)**	(0.47)
	{0}	{0}	**{0}**	{0}
Bacteria	0.04	0.04	**0.03**	0.03
	[0.01, 0.06]	[0.01, 0.06]	**[0, 0.05]**	[0, 0.05]
	(0.003*)	(0.003*)	**(0.03*)**	(0.02*)
	{0.04}	{0.04}	**{0.03}**	{0.03}
Formaldehyde	0.03	0.03	**0.03**	0.03
	[0, 0.06]	[0, 0.06]	**[0, 0.05]**	[0, 0.06]
	(0.03*)	(0.03*)	**(0.03*)**	(0.03*)
	{0.03}	{0.03}	**{0}**	{0}
CO	0.02	0.03	**0.02**	0.01
	[0, 0.05]	[0, 0.05]	**[-0.01, 0.04]**	[-0.01, 0.04]
	(0.03*)	(0.03*)	**(0.16)**	(0.37)
	{0.03}	{0.03}	**{0.02}**	{0.01}
$PM_{2.5}$		0.001		
		[0, 0.03]		
		(0.58)		
		{0}		
TVOC			**0.04**	
			[0.02, 0.06]	
			(< 0.001*)	
			{0.05}	

CO_2				0.05
				[0.02, 0.08]
				(0.002*)
				{0.04}
AIC	116736.1	116733.0	**116723.9**	116728.1
AIC Weightage	0.2%	1.0%	**87.7%**	11.1%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 2 in Table 5-12 with an AIC value of 116723.9, carrying 87.7% of the cumulative weight. The Model 2 intercept (fixed variables = 0) is at 12190.0 (95% CI [11481.2, 12898.9], t (6380) = 33.7, $p < .001$). The predicted values from Model 2 showed a positive effect of TVOC (standardised beta = 0.04, $p < .001$) on the time taken to complete. The effect size of Model 2 showed a small effect. The linear relationship between the time taken to complete and the concentration levels of TVOC is shown in Figure 5-24. As the concentration levels of TVOC increase, more time is taken to respond to the stimuli.

A)



B)

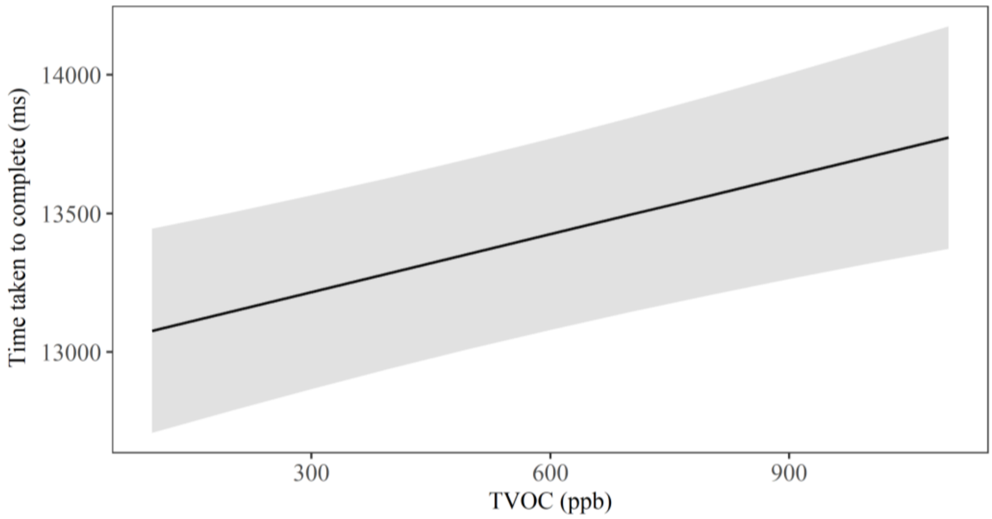


Figure 5-24. Effect of TVOC on the reaction time (ms) in model 2. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.5 Speed of Information Processing

5.3.5.1 Two-column Addition Test

The measurement outcome variables comprised correct and incorrect answers. Each of the outcome variables is associated with dependent variables. Separate sets of hierarchical models were analysed based on the dependent variables, time, correct entries, and interactions of time variants. The best-fitted model involves the time taken to generate a correct answer that satisfies the Bonferroni adjusted null hypothesis shown in Table 5-13.

Table 5-13. Linear mixed regression model testing the effect of IAQ parameters on time taken for correct answers and treating 90 participants as a random intercept.

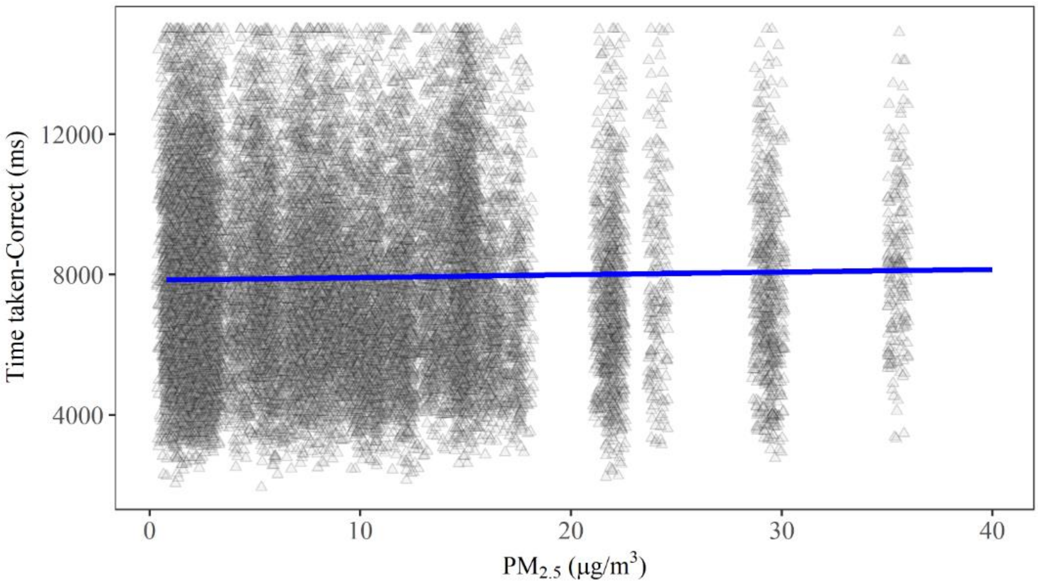
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	**Model 1**	Model 2	Model 3
Scaled Week	-0.09	**-0.08**	-0.09	-0.09
	[-0.1, -0.07]	**[-0.09, -0.07]**	[-0.1, -0.07]	[-0.1, -0.07]
	(< 0.001*)	**(< 0.001*)**	(< 0.001*)	(< 0.001*)
	{0.09}	**{0.08}**	{0.09}	{0.09}
Fungi	-0.001	**-0.01**	-0.001	-0.001
	[-0.02, 0.01]	**[-0.03, 0]**	[-0.02, 0.01]	[-0.02, 0.01]
	(0.57)	**(0.14)**	(0.49)	(0.56)
	{0}	**{0.01}**	{0}	{0}
Bacteria	-0.001	**-0.001**	-0.001	-0.001
	[-0.02, 0.01]	**[-0.02, 0.01]**	[-0.02, 0.01]	[-0.02, 0.01]
	(0.77)	**(0.74)**	(0.63)	(0.8)
	{0}	**{0}**	{0}	{0}
Formaldehyde	-0.001	**-0.001**	-0.001	-0.001
	[-0.02, 0.01]	**[-0.02, 0.01]**	[-0.02, 0.01]	[-0.02, 0.01]
	(0.44)	**(0.46)**	(0.44)	(0.44)
	{0}	**{0}**	{0}	{0}
CO	-0.001	**-0.001**	-0.001	-0.001
	[-0.02, 0.01]	**[-0.02, 0.01]**	[-0.02, 0.01]	[-0.02, 0.01]
	(0.3)	**(0.33)**	(0.23)	(0.38)
	{0}	**{0}**	{0}	{0}
$PM_{2.5}$		**0.02**		
		[0.01, 0.03]		
		(0.002*)		
		{0.02}		
TVOC			0.001	
			[-0.01, 0.02]	
			(0.26)	
			{0}	

CO_2				-0.001
				[-0.02, 0.02]
				(0.8)
				{0}
AIC	357551.4	**357540.1**	357554.9	357554.0
AIC Weightage	0.5%	**99.5%**	0%	0%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 1 in Table 5-13 with an AIC value of 357540.1, carrying 99.5% of the cumulative weight. The Model 1 intercept (fixed variables = 0) is at 8090.7 (95% CI [7608.6, 8572.9], t (19549) = 32.9, $p < .001$). The predicted values from Model 1 showed a positive effect of $PM_{2.5}$ (standardised beta = 0.02, p= 0.002) on time taken for correct answers. The effect size of Model 1 showed a small effect. The linear relationship between the time taken for correct answers and the concentration levels of $PM_{2.5}$ is shown in Figure 5-25. As the concentration levels of $PM_{2.5}$ increase, more time is taken to process the information to obtain the correct answer.

A)



B)

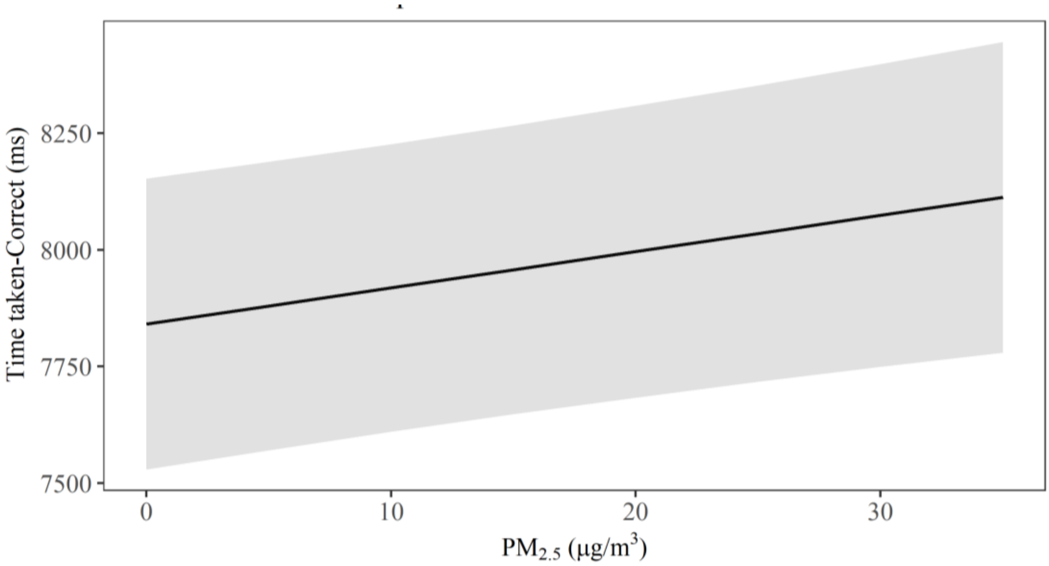


Figure 5-25. Effect of $PM_{2.5}$ on the reaction time (ms) in model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.7 Fluid Intelligence

5.3.7.1 Matrix Rotation Test

The measurement outcome variables comprised the study time (time viewing the target image), reaction time (time from the appearance of the response image to pressing a button), and correct responses. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, study time, reaction time, correct entries, and interactions of correct entries. The best-fitted model involves the reaction time for correctly identifying the presence of rotation that satisfies the Bonferroni adjusted null hypothesis shown in Table 5-14.

Table 5-14. Linear mixed regression model testing the effect of IAQ parameters on reaction time (ms) and treating 90 participants as a random intercept.

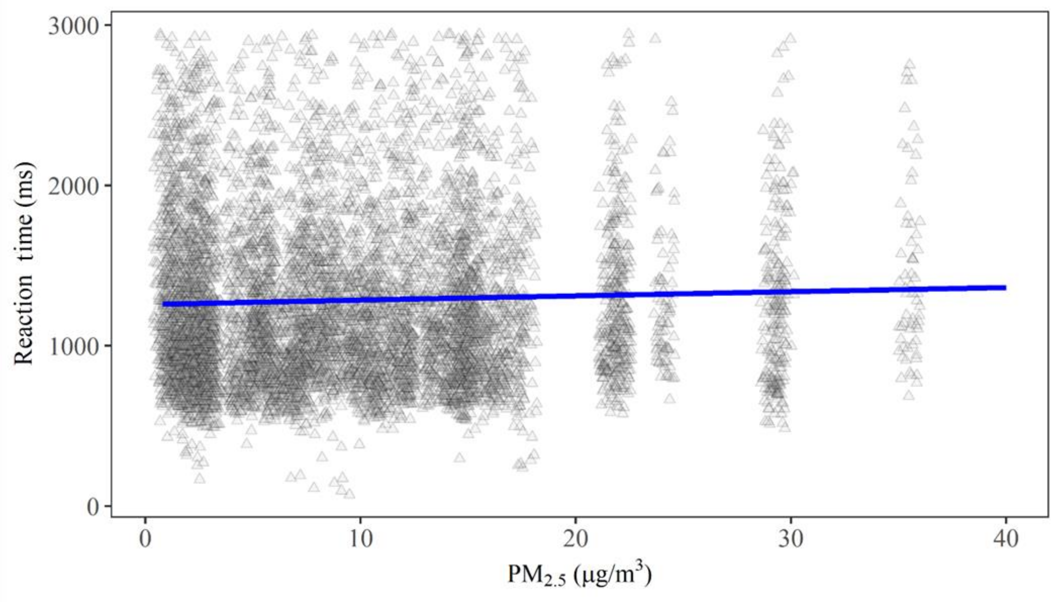
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	**Model 1**	Model 2	Model 3
Scaled Week	-0.22	**-0.21**	-0.22	-0.06
	[-0.24, 0.20]	**[-0.23, -0.19]**	[-0.24, -0.20]	[-0.09, -0.02]
	(< 0.001*)	**(< 0.001*)**	(< 0.001*)	(< 0.001*)
	{0.24}	**{0.23}**	{0.24}	{0.06}
Fungi	-0	**-0.01**	-0	0.02
	[-0.02, 0.02]	**[-0.04, 0.01]**	[-0.03, 0.02]	[-0.01, 0.06]
	(0.97)	**(0.27)**	(0.72)	(0.99)
	{0}	**{0.01}**	{0}	{0.02}
Bacteria	-0	**-0**	-0.01	0
	[-0.03, 0.02]	**[-0.03, 0.02]**	[-0.03, 0.01]	[-0.03, 0.05]
	(0.60)	**(0.58)**	(0.30)	(0.57)
	{0}	**{0}**	{0.01}	{0}
Formaldehyde	-0	**-0**	-0	-0.11
	[-0.03, 0.02]	**[-0.03, 0.02]**	[-0.03, 0.02]	[-0.15, -0.07]
	(0.88)	**(0.94)**	(0.86)	(0.89)
	{0}	**{0}**	{0}	{0.10}

CO	0	**0.01**	0	0.03
	[-0.01, 0.03]	**[-0.01, 0.03]**	[-0.02, 0.02]	[-0.01, 0.06]
	(0.44)	**(0.36)**	(0.80)	(0.67)
	{0}	**{0.01}**	{0}	{0.03}
$PM_{2.5}$		**0.04**		
		[0.02, 0.06]		
		(< 0.001*)		
		{0.04}		
TVOC			0.03	
			[0.01, 0.05]	
			(0.005*)	
			{0.03}	
CO_2				-0.11
				[-0.15, -0.07]
				(0.42)
				{0.10}
AIC	115820.5	**115809.2**	115819.8	115825.0
AIC Weightage	0.3%	**99.1%**	0.5%	0%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 1 in Table 5-14 with an AIC value of 115809.2, carrying 99.1% of the cumulative weight. The linear relationship between reaction time and $PM_{2.5}$ is shown in Figure 5-26. As the concentration levels of $PM_{2.5}$ increase, the time is taken to identify the pattern also increases. The model 1 intercept (fixed variables = 0) is at 2.65 (95% CI [1.15, 4.15], t (7743) = 3.47, p < .001). The predicted values from Model 1 showed a significant positive effect of $PM_{2.5}$ (standardised beta = 0.04, p <0.001) on reaction time with a small effect.

A)



B)

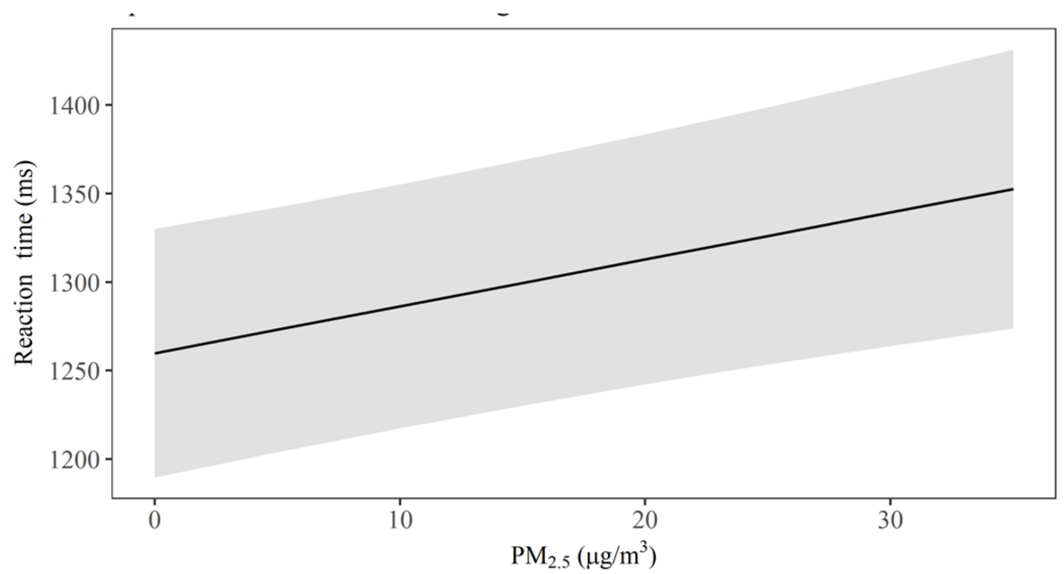


Figure 5-26. Effect of $PM_{2.5}$ on the reaction time in model 1. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.7.2 Mental Rotation Test

The measurement outcome variables were the total time to complete the test and correct responses. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, time taken to complete, and correct entries. The best-fitted model involves time taken to identify the similarities among the figures correctly satisfies the Bonferroni adjusted null hypothesis shown in Table 5-15.

Table 5-15. Linear mixed regression model testing the effect of IAQ parameters on time taken for correct entries and treating 90 participants as a random intercept.

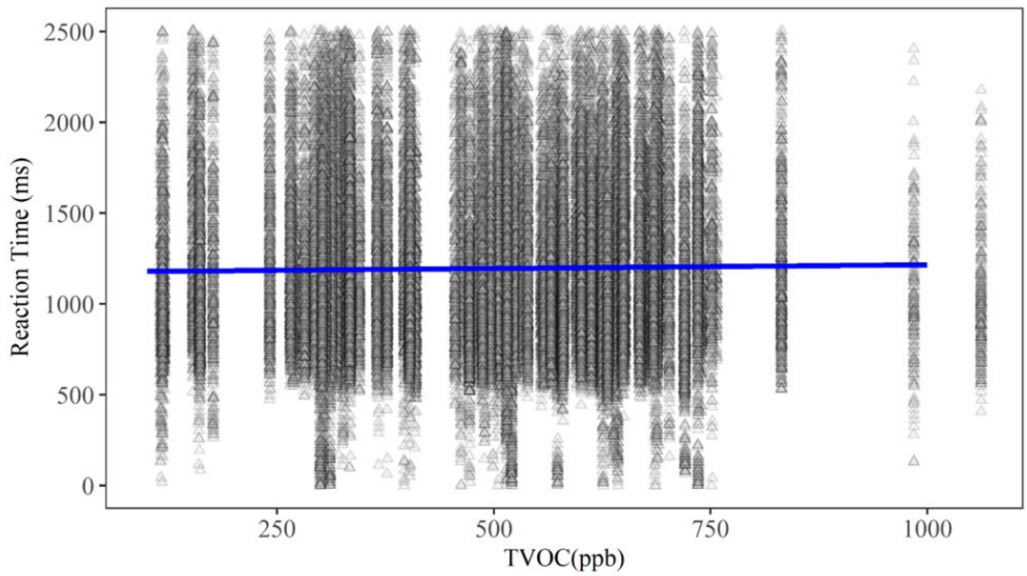
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	Model 1	**Model 2**	Model 3
Scaled Week	-0.16	-0.16	**-0.16**	-0.16
	[-0.17, -0.15]	[-0.17, -0.15]	**[-0.17, -0.15]**	[-0.17, -0.15]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.16}	{0.15}	**{0.16}**	{0.15}
Fungi	0	-0.01	**0**	0.02
	[-0.01, 0.01]	[-0.01, 0.01]	**[-0.01, 0.01]**	[-0.01, 0.01]
	(0.48)	(0.5)	**(0.69)**	(0.47)
	{0}	{0}	**{0}**	{0}
Bacteria	0	0	**-0.01**	0
	[-0.01, 0.01]	[-0.01, 0.01]	**[-0.01, 0.01]**	[-0.01, 0.01]
	(0.93)	(0.93)	**(0.** 57**)**	(0.96)
	{0}	{0}	**{0}**	{0}
Formaldehyde	-0.02	-0.02	**-0.02**	-0.02
	[-0.03, 0.01]	[-0.03, 0.01]	**[-0.03, 0.01]**	[-0.03, 0.01]
	(< 0.001*)	(< 0.001*)	**(< 0.001*)**	(< 0.001*)
	{0.02}	{0.02}	**{0.02}**	{0.02}
CO	-0.01	-0.01	**-0.02**	-0.01
	[-0.02, 0]	[-0.02, 0]	**[-0.02, -0.01]**	[-0.02, 0]
	(0.01)	(0.01)	**(0.01)**	(0.01)
	{0.01}	{0.01}	**{0.01}**	{0.01}

$PM_{2.5}$		0		
		[-0.01, 0.01]		
		(0.97)		
		{0}		
TVOC			**0.01**	
			[0.01, 0.02]	
			(< 0.001*)	
			{0.01}	
CO_2				0
				[-0.01, 0.01]
				(0.87)
				{0}
AIC	806583.8	806586.4	**806581.3**	806590.8
AIC weightage	20.8%	5.5%	**73.1%**	0.6%

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is model 2 in Table 5-15 with an AIC value of 836190.0, carrying 98.6% of the cumulative weight. The model 2 intercept (fixed variables = 0) is at 1274.6 (95% CI [1217.7, 1331.5], $t(54043) = 43.9$, $p < .001$). The predicted values from Model 2 showed a significant positive effect of TVOC (standardised beta = 0.01, $p < 0.001$) on time taken for correct entries. The effect size of Model 2 showed a small effect size. The linear relationship between reaction time and TVOC is shown in Figure 5-27. As TVOC increases, the time taken to identify similarities between figures increases.

A)



B)

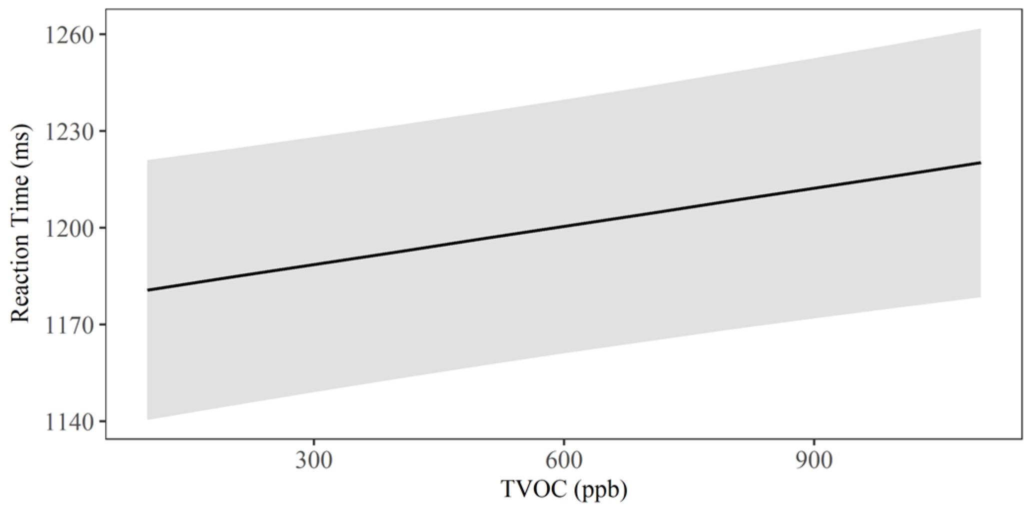


Figure 5-27. Effect of TVOC on the reaction time (ms) in model 2. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.3.8 Planning

5.3.8.1 TOL-R Test

The TOL-R test was bound by a time limit and the number of clicks. The measurement outcome variables comprised failure, number of clicks, time limit, and success. Each of the outcome variables is associated with dependent variables. Therefore, separate sets of hierarchical models were analysed based on the dependent variables, success, time taken, failure, and successful interactions. The best-fitted model involves the success of recognising the pattern that satisfies the Bonferroni adjusted null hypothesis shown in Table 5-16.

Table 5-16. Linear mixed regression model testing the effect of IAQ parameters on time taken for failure and treating 90 participants as a random intercept.

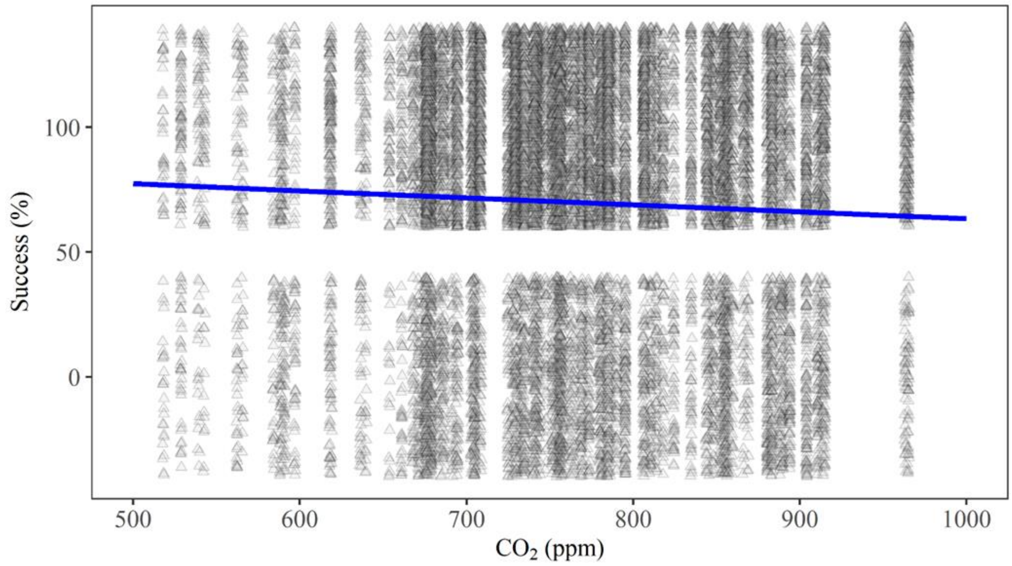
	Model parameters: standardised estimate, [95% standard confidence interval], (p-value), {effect size}			
	Model 0	Model 1	Model 2	**Model 3**
Scaled Week	0.09	0.09	0.09	**0.07**
	[0.07, 0.1]	[0.07, 0.1]	[0.07, 0.1]	**[0.06, 0.09]**
	(< 0.001*)	(< 0.001*)	(< 0.001*)	**(< 0.001*)**
	{0.08}	{0.08}	{0.08}	**{0.07}**
Fungi	0	0	0	**0**
	[-0.03, 0.01]	[-0.03, 0.01]	[-0.02, 0.01]	**[-0.03, 0.01]**
	(0.39)	(0.51)	(0.69)	**(0.34)**
	{0}	{0}	{0}	**{0}**
Bacteria	0	0	0	**0**
	[-0.02, 0.02]	[-0.02, 0.02]	[-0.01, 0.03]	**[-0.01, 0.03]**
	(0.97)	(0.96)	(0.45)	**(0.34)**
	{0}	{0}	{0}	**{0}**
Formaldehyde	0	0	0	**0**
	[-0.02, 0.02]	[-0.02, 0.02]	[-0.02, 0.02]	**[-0.02, 0.02]**
	(0.99)	(0.98)	(0.95)	**(0.96)**
	{0}	{0}	{0}	**{0}**
CO	-0.02	-0.02	-0.02	**0**

	[-0.04, -0.01]	[-0.04, -0.01]	[-0.03, 0]	**[-0.02, 0.02]**
	(0.01*)	(0.01*)	(0.06)	**(0.5)**
	{0.02}	{0.02}	{0.01}	**{0}**
$PM_{2.5}$		0		
		[-0.02, 0.01]		
		(0.59)		
		{0}		
TVOC			-0.03	
			[-0.05, -0.01]	
			(< 0.001*)	
			{0.03}	
CO_2				**-0.05**
				[-0.08, -0.03]
				(< 0.001*)
				{0.04}
AIC	167019.6	167025.3	167017.9	**167008.1**
AIC Weightage	0.3%	0.1%	0.7%	**98.9%**

* denotes statistical significance for p-values less than 0.0125 after the Bonferroni adjustment.

The best fitted linear regression model is Model 3 in Table 5-16 with an AIC value of 167008.1, carrying 98.9% of the cumulative weight. The Model 3 intercept (fixed variables = 0) is at 93.0 (95% CI [82.3, 103.7], $t(16071) = 17.0$, $p < .001$). The predicted values from Model 3 showed a negative effect of CO_2 (standardised beta = -0.05, $p < 0.001$) on the success of recognising the pattern. The effect size of Model 3 showed a small effect. The linear relationship between the percentage of success and the level of CO_2 is shown in Figure 5-28. As CO_2 increases, fewer successes were observed in recognising the correct pattern.

A)



B)

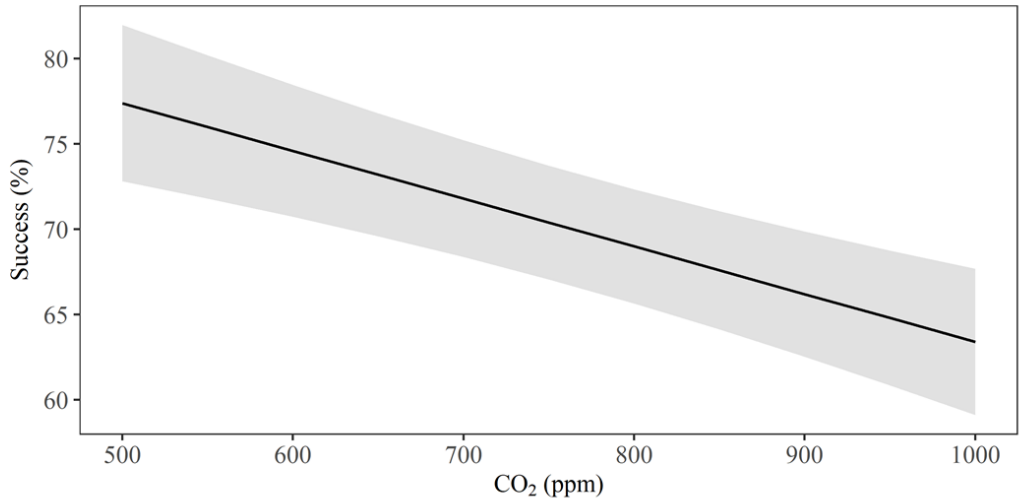


Figure 5-28. Effect of CO_2 on the percentage of success in model 3. A) Linear mixed regression line with the data points. B) Linear mixed regression line without the data points. The shaded band represents a confidence interval of 95% of the data.

5.4 Discussion

The study investigated the effects of reducing IAQ pollutants, $PM_{2.5}$ and TVOC with MERV 14 and carbon filter, respectively, over 6 IAQ conditions (HV (1 ACH), LV (0.5 ACH), HV-PM, HV-PM-C, and HV-C), on adult's cognitive health in 7 domains of higher-order executive functions. While statistically significant effects of CO_2 (treated as a marker for other pollutants) were found, these effects did not make up a large proportion of the AIC weightage for any of our models. This is in contrast to Allen et al. (2016)findings which showed significant effects of CO_2 on cognitive function. This could be because Allen's paper considered CO_2 as an IAQ pollutant ranging to a maximum of 1420 ppm compared to approximately 900 ppm in this study.

The current practice to improve the health of the building, the green mark criteria on IAQ performances include installing a particle filter (at least MERV 13 rating) at the air handling unit, use of low VOC paint in the interior walls, use of environmentally friendly adhesives, and conducting an IAQ audit once every 3 years (Building and Construction Authority, 2016). Previous studies have shown that the primary source of TVOC is occupants (Veres et al., 2013; C. Wang et al., 2014a, 2014b; Weschler, 2016). Hence, reducing building materials that emit VOCs is not sufficient to improve IAQ. This has been shown in Figure 3-11 (Chapter 3, section 3.6), where the concentration of VOC without the carbon filters was much higher. These VOCs are unlikely to be emitted from the paintwork or adhesives in the chamber because most off-gassing occurs within the first six months. Moreover, in this study, the association found in TVOC concentration levels complements Allen et al. (2016) findings.

It is well documented that $PM_{2.5}$ and ultrafine particles can break the brain-blood barrier and deposit in the brain. In the long run, it is known to cause neurodegenerative diseases (Manisalidis et al., 2020). In the current study with short-term exposure, a decrement of 10 $\mu g / m^3$ in $PM_{2.5}$ showed a reduction in speed of information processing by 77.7ms. A decrement of 10 ppb in TVOC showed a reduction in reaction time to BCST (1.6ms), Time-wall (0.02%), Trail making (7.9 ms) and an increment of 1.4% in creativity. A decrement of 10 ppm in CO_2 (bio-effluent) showed a 0.3% increase in success rate.

An interesting finding from the current study was that inhibitory control was dominated by the influence of combined TVOC and $PM_{2.5}$ concentration levels. In addition, fluid intelligence and working memory showed a dominant influence of $PM_{2.5}$ and TVOC. A decrement of 10 $\mu g/m^3$ and 10 ppb in $PM_{2.5}$ and TVOC, respectively, showed a reduction of 25.5ms [$PM_{2.5}$] and 0.4ms [TVOC] fluid intelligence, 7.5ms [$PM_{2.5}$] and 2.0ms [TVOC] in working memory, 1.9ms [$PM_{2.5}$] and 2.0ms [TVOC] in attention and 21.2ms [$PM_{2.5}$] and 0.1ms [TVOC] in response inhibition. The combined influence was observed in reaction for all EF domains listed above.

It can be deduced that a combination of IAQ pollutants can affect higher order executive function, leading to critical cognitive health problems. Memory loss is one of the main symptoms indicating dementia, and studies have shown that $PM_{2.5}$ is one of the aggravating factors (J. C. Chen et al., 2015; C. Lang, 1989; Sullivan et al., 2021). The data from the current study potentially shows that TVOC could also be a possible factor in the loss of memory.

This study showed that it is essential for buildings to install air filters that target PM and TVOC in the mechanical ventilation system on top of the measures taken for green mark buildings and the importance of better air quality. It also encourages relevant authorities to include high-grade filters in green buildings for better cognitive health and building health. Hence the application of the filters should not be removed from the consideration when it comes to cutting costs or moving towards a net-zero energy building.

5.5 Conclusion

Adding both a particle filter and a carbon filter to the HVAC system of a room improves IAQ, and as a result, we find improvements in multiple cognitive processes. In addition, adopting both types of filters could result in a healthy economy with less absenteeism and more productivity from employees.

Chapter 6

Impact of IAQ on Electrophysiological Responses

The chapter attempts to understand the reasons for the cognitive effects observed when being exposed to the IAQ parameters, $PM_{2.5}$, TVOC, and CO_2 (bio-effluent). The study adopts data exploration to understand the underlying mechanism that causes the effects observed in Chapter 5. This is achieved by measuring the electrophysiological responses via EEG headsets on participants with cognitive test battery task as the stimuli for 30 minutes. The data analysis involves examining the 4 EEG frequency bands: delta rhythm, theta rhythm, alpha rhythm, and beta rhythm. Further statistical analysis on engagement indices was performed to model the combination of different EEG rhythms to understand the implications of the IAQ association with cognitive health.

6.1 Introduction

Pollutants such as $PM_{2.5}$ and VOCs have been shown to enter the brain, and CO_2 can potentially affect brain blood oxygenation levels. These pollutants also reduce an individual's performance at specific tasks (see chapter 5). There is an assumed link where pollutants cause a reduction in task performance by affecting brain activity.

6.1.1 Studying Brain Activity

At the neuronal level, an action potential (usually when a stimulus is present) depolarises the presynaptic terminal releasing neurotransmitters into the synaptic cleft, which binds to the postsynaptic receptors generating postsynaptic current. The postsynaptic current causes excitatory (increases the likelihood of neuron firing an action potential) or inhibitory (decreases the likelihood of neuron firing an action potential) postsynaptic potentials that change the excitability of the postsynaptic cell. This synaptic activity is observed within a fraction of a millisecond after generating a presynaptic action potential ('Neuroscience', 2012). The synchronised electrical activity among populations of neurons generates superficial rhythmic electrical activity that could be continuously monitored using an electroencephalogram (EEG) headset. The EEG signals are recorded as a time-varying difference in voltage between the active electrode and the reference electrode placed on the scalp.

6.1.2 Engagement indices

A common practice to analyse EEG signals is to decompose into four power spectral density (PSD) bands, i.e., delta, theta, alpha, and beta (see Figure 6-1) or by taking the ratios between the PSD bands known as engagement indices, to measure the changes in cognitive states (Makeig & Inlow, 1993).

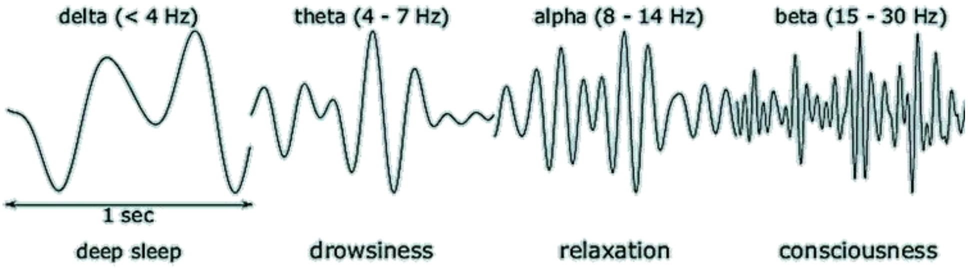


Figure 6-1. EEG frequency ranges typically recorded. Theta band activity usually indicates drowsiness, but at the frontal sites, it indicates mental effort. It was adapted from Roberts et al. (2016).

Pope et al. (1995) examined several possible combinations of EEG power spectra in complex tasks and found an index that reflects mental workload (here referred to as engagement index 1). Gevins et al. (Gevins et al., 1997; Gevins & Smith, 2003; Smith & Gevins, 2005) studied task load or workload during various tasks and whether spectral changes were consistent among participants over time (here referred to as engagement index 2). Yamada (1998) recommended an index that assesses mental effort (here referred to as engagement index 3). These have been collectively described as engagement indices. Other studies that examined the engagement indices showed similar outcomes in terms of cognitive states (Gevins et al., 1997; Pope et al., 1995; Yamada, 1998). These engagement indices can be used to classify participants' cognitive states (like goal maintenance and effort regulation) and indicate how cognitively engaged they were in the task. In addition, the engagement index accommodates the irregularity of changes observed within the EEG frequency bands.

Hockey (2013) categorised possible stressors that can affect the task, for instance, cognitive, somatic, and environmental events. The prolonged presence of stressors (such as noise, heat, or air quality) can influence the efficiency of goal maintenance by introducing fatigue. Fatigue is commonly known as the feeling of constant tiredness or weakness that makes an individual sleep, which is different from mental fatigue. Mental fatigue is caused by prolonged cognitive activity and serves as an interrupting factor when the behaviour is not rewarding (Hockey, 2013). In prolonged tasks, mental fatigue can cause changes to maintain an aspect of performance at the expense of another; for instance, maintaining correct responses in a task compromises the reaction time (Rabbitt & Vyas, 1981). Hence, in this study context, mental fatigue is discussed.

An effort is a psychological state that agrees to the regulatory cost; if an individual requires a high effort to maintain a goal, it may be pursued if anticipated benefits or rewards are sufficiently high (Hockey, 2013). A previous study showed that rats worked harder to receive greater rewards to maintain task performance (Walton et al., 2006). As an effort-driven interruption, fatigue increases the strain on attention to maintain the goal (Hockey, 2013). Hence, more mental effort (effort regulation) is required to control mental fatigue (goal maintenance) under various stressors, which accounts for task performance stability in highly motivated participants subjected to stressors.

6.1.3 Current study

Previous studies that investigated the health of buildings assessed indoor thermal comfort (Shan & Yang, 2020; Yao et al., 2008), light comfort (Lu et al., 2020) and sleep quality (Lan et al., 2014; Liao et al., 2021) on occupants by using EEG. However, no studies have reported the association of electrophysiological responses with IAQ. Therefore, this study explores the possibility of associating IAQ pollutants ($PM_{2.5}$, TVOC, and CO_2) effects on cognitive functions with the electrophysiological responses in an office-like environment chamber.

6.2 Methods

The methodology described in Chapter 3 is summarised in Figure 6-2. The study protocol involves the same study population of 90 participants. The EEG segment in Figure 6-2 indicates the duration given to participants to calibrate the headset and obtain 100% connectivity in all 14 electrodes before administrating the stimulus (cognitive test battery, Chapter 5).

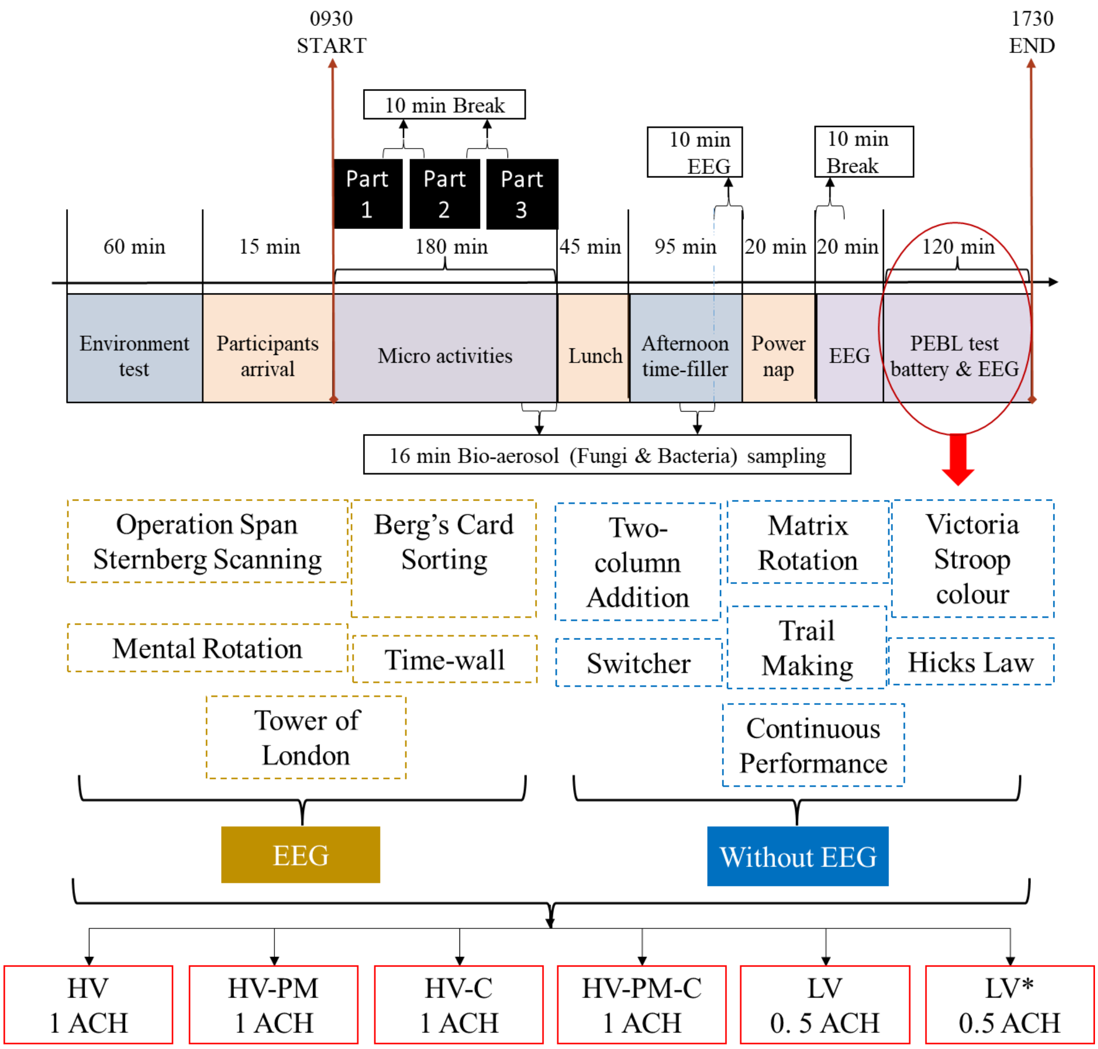


Figure 6-2. Participant's daily protocol. Adapted from section 3.4.2, it highlights the EFs involved in the EEG assessments of the PEBL. The corresponding IAQ study conditions (HV – high ventilation (1 ACH), LV – low ventilation (0.5 ACH), PM – PM filter inserted, and C – carbon filter inserted) in red boxes indicates that the same protocol was administered for all conditions.

6.2.1 PEBL Test Battery as Stimulus

The psychology experiment building language (PEBL) test battery was used as a stimulus. Participants were exposed to 6 different tasks for 30 minutes in Figure 6-3. This subset of the cognitive test battery (as shown in Figure 6-3) is administered in Chapter 5. The subset covers each of the EFs domains. Arguably, BCST and Time-wall assess both cognitive flexibility and control (Mueller & Piper, 2014). Participants were reminded before the start of the test battery to give their best at every task and be fast and accurate with their responses.

PEBL task	Executive function domains
Operation Span	Working memory
Sternberg Scanning	Working memory
BCST	Cognitive flexibility & control
TOL	Planning
Time-wall	Cognitive flexibility & control
Mental Rotation	Fluid intelligence

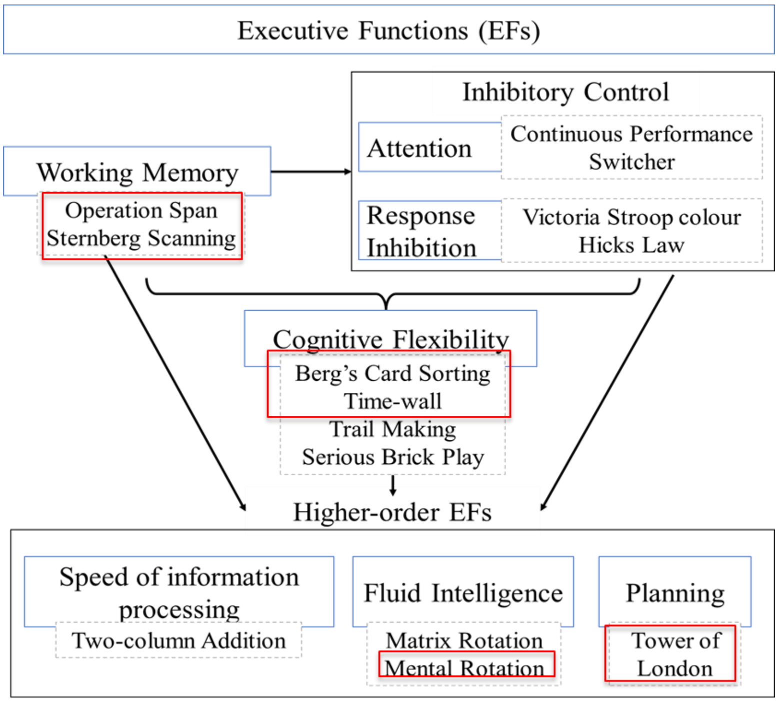


Figure 6-3. The list of PEBL tasks was administered for 30 minutes in one seating and assessed cognitive domains. The red box highlights the selected PEBL test battery administered with the EEG headsets.

6.2.2 Data Acquisition

The electrophysical responses were acquired using a commercially available research-oriented wireless headset, Emotiv EPOC+ (Emotiv Systems Inc., USA). The headset has 14 channels designed with active biopotential sensors with gold plated electrodes based on the international 10-20 system of electrode placement: (i) frontal lobe: AF3, AF4, F3, F4, F7, F8, FC5, and FC6; (ii) temporal lobe: T7 and T8; (iii) parietal lobe: P7 and P8; and (iv) occipital lobe: O1 and O2 (Lievesley et al., 2011) as shown in Figure 6-4. In addition, two reference channels, CMS (Common Mode Sense) and DRL

(Driven Right Leg) were recorded for rejection of common-mode artefacts and electrical noise.

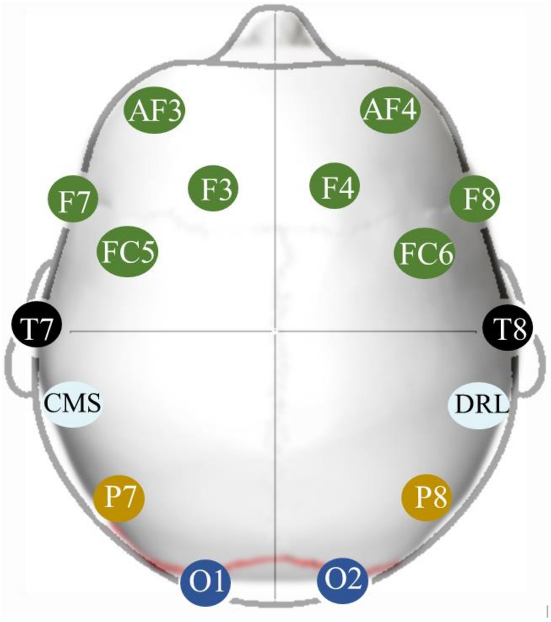


Figure 6-4. The electrode positions on the participant's scalp for the EMOTIV-EPOC headset. The electrodes are colour coded to indicate brain lobe classification; green for the frontal lobe, black for the temporal lobe, gold for the parietal lobe, and blue for the occipital lobe. CMS and DRL indicate reference channels.

In addition, sensors in the headband collected motion and axis data. Pre-soaked saline sponges allowed electrical connectivity between the electrodes and the scalp's surface. The EEG signals were recorded at a sampling frequency of 128 Hz and 16-bit analogue to digital resolution. The headset collected the electrophysical responses in 0.16 – 43 Hz bandwidth and digital notch filters at 50 Hz. All collected information was transferred via Bluetooth to a USB receiver at a 2.4GHz band to a working station. This information was then recorded using EMOTIV PRO (an integrated software built for EPOC+), which has a real-time display of sensor contact quality and packet count functionality to prevent data loss. The raw data were exported in EDF file format for pre-processing.

6.2.3 Data pre-processing pipeline

The EEG data is prone to artifacts that cause unwanted EEG data. Hence, pre-processing the raw data required removing artifacts such as noise, eye blinks, and muscle activities. Data pre-processing pipeline were conducted in MATLAB (version 9.9) based toolbox EEGLAB (v2020.0) (Delorme & Makeig, 2004). The EEG signals from 14 channels were selected, and channel locations from EMOTIV were imported into EEGLAB. The data were then high pass filtered at 0.5 Hz, setting a transition band of 0.75 Hz to 1.25 Hz. This filtered out ultralow frequency artifacts such as heart signals or skin potentials (X. Jiang et al., 2019; Kappenman & Luck, 2010). No channels were removed from the cleaning process. Instead, the artifact subspace reconstruction (ASR) algorithm rejected bad portions of the data. ASR repeatedly calculates principal component analysis on covariance matrices to detect artifacts (Blum et al., 2019). It finds the clean portion of data (calibration data), computes the principal component analysis of extracted components' standard deviation, and rejects regions exceeding 10 times the standard deviation of the calibration data (Delorme et al., 2021). Additional removal of bad data periods was kept at default measurements of 25% out-of-bound channels. At this stage of the pre-processing, neural artifacts such as line and channel noise have been removed. The data were re-referenced to the average of CMS and DRL (reference electrodes). This was followed by removing the baseline from the dataset.

The removal of non-neural artifacts such as signal deviation caused by blinks, muscle movement, and heart signals is commonly performed by semi-automatic identification and removal of the time segments in the data when the artifacts are present. However, an automated approach was taken due to the high volume of data. The automation utilises independent component analysis (ICA), which involves identifying (ICA decomposition) and removing artifact-related activity from the dataset. ICA decomposition was performed independently on each dataset using the ICA algorithm, Runica (SCCN & UC San Diego, 2020). In addition, the ICLabel plugin was used to classify the artefactual ICA components into 6 categories of components brain, muscle, eye, heart, line noise, channel noise, and other (Pion-Tonachini et al., 2019).

The eye and muscle movement artifacts were flagged if those components had more than a 90% probability of being classified under the eye and muscle artifact category. The continuous data were split into epochs of 2 seconds (3600 epochs). Epochs containing artifacts flagged under ICA were removed using a voltage-based threshold of -100 mV and 100 mV. This was followed by filtering the data using Hamming window and Sinc function finite-impulse response (FIR) filter of a low-pass filter, 30 Hz. ICA decomposition was performed again using the runica algorithm to concatenate all datasets and identify any decomposition features that are not stable across decompositions that should not be interpreted.

After completing the EEG signal pre-processing, the power spectral densities (PSD) were computed using the Spectopo and Spectra function from the EEGLAB, using Welch's power spectral density estimate to obtain the power estimates from the raw data. The analysis calculated the mean power spectral densities into different EEG frequency bands: delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), and beta (13-30 Hz). The average power spectral densities were calculated across all 14 electrodes and obtained a global average for each frequency band per electrode used in the subsequent statistical analysis.

A file corresponds to a participant (90 in total) with a minimum of 420 data points (14 electrodes x 30minutes) for each session. The total number of files for all 3 rounds before pre-processing was 416 (124 files were removed due to technical issues), and after pre-processing, 385 files, with 31 files rejected in the process. Therefore, each of the pre-processed files consists of 201,600 (14 electrodes x 4 frequency bands x 3600 epochs) data points, and a total of 77.6 million data points (201,600 x 385) were analysed.

6.2.4 Analysis

In this study, 3 engagement indices were explored to understand the effects of IAQ pollutants on cognitive processes. Engagement Index 1 reflects the process of information gathering, visual scanning, and sustained attention. Engagement Index 2 reflects executive functioning, and Engagement Index 3 can be used to measure task-related attention (Berka et al., 2007; McMahan et al., 2015; Nassef et al., 2009).

- Index 1: defined as $\frac{\text{Beta power}}{\text{Alpha power} + \text{Theta power}}$ (Pope et al., 1995)
- Index 2: defined as $\frac{\text{Frontal Theta power}}{\text{Parietal Alpha power}}$ (Gevins & Smith, 2003)
- Index 3: defined as $\text{Average Frontal Theta power}$ (Yamada, 1998)

The statistical analysis presented in Chapter 3; section 3.5 is slightly modified for data exploration analysis. Instead of using AIC to choose the best fitting model, all 3 models (Model 1, Model 2, and Model 3) were interpreted. Only the experimentally controlled, statistically significant (p-value <0.05) IAQ parameters were discussed. This is because the motive of data exploration is to understand the possible biological mechanism present for short-term exposure to $PM_{2.5}$, TVOC, and CO_2 (bio-effluent). The base model (Model 0) was not interpreted as the covariates were not experimentally controlled.

6.3 Results

The data were first analysed based on the individual EEG frequencies (delta, theta, alpha, and beta) see sections 6.3.1, 6.3.2, 6.3.3, and 6.3.4. Literature showed that neuronal activity in different brain regions (frontal, temporal, parietal, and occipital) could indicate separate mental processes. Therefore, the predicted trends observed from sections 6.3.1, 6 3.2, and 6 3.3 are further divided into the 4 brain regions (modelled as an interaction of each brain region multiplied by the IAQ parameter of concern) for closer examination of the associations of IAQ parameters presented in sections 6.3.1.1, 6.3.2.1, and 6.3.3.1. The slope of a line fitted to the regions is estimated using a difference quotient via emmeans::emtrends (). As an overall analysis, section 6.3.5 implements engagement indices to determine the association of cognitive states to IAQ parameters.

For each section, the results are presented using a hierarchical linear regression model summarised in a regression table with standardised estimates, 95% confidence intervals, p-value, and effect size, and the table of estimates of slopes for the specific brain regions.

6.3.1 Delta Rhythm (1 Hz – 4 Hz)

Table 6-1. Linear regression model testing the effect of IAQ parameters on delta waveform frequency and treating participants as a random intercept. Model parameters: standardised estimate, [95% standard confidence interval], (p-value), and {effect size}.

	Model 0	Model 1	Model 2	Model 3
Scaled Week	-0.001	-0.001	-0.001	-0.02
	[-0.04, 0.02]	[-0.03, 0.03]	[-0.03, 0.03]	[-0.05, 0.01]

	(0.58)	(0.95)	(0.88)	(0.15)
	{0}	{0}	{0}	{0.02}
Fungi	0.03	0.01	0.01	0.03
	[-0.01, 0.06]	[-0.02, 0.05]	[-0.02, 0.05]	[-0.01, 0.06]
	(0.12)	(0.44)	(0.37)	(0.1)
	{0.02}	{0.01}	{0.01}	{0.03}
Bacteria	-0.001	-0.001	-0.01	0.001
	[-0.04, 0.03]	[-0.04, 0.03]	[-0.05, 0.02]	[-0.03, 0.03]
	(0.83)	(0.83)	(0.38)	(0.92)
	{0}	{0}	{0.01}	{0}
Formaldehyde	0.01	0.01	0.02	0.01
	[-0.02, 0.05]	[-0.02, 0.05]	[-0.02, 0.05]	[-0.02, 0.05]
	(0.43)	(0.42)	(0.32)	(0.42)
	{0.01}	{0.01}	{0.02}	{0.01}
CO	-0.03	-0.03	-0.04	-0.02
	[-0.06, 0]	[-0.06, 0]	[-0.07, -0.01]	[-0.05, 0.02]
	(0.06)	(0.06)	(0.01*)	(0.33)
	{0.03}	{0.03}	{0.04}	{0.01}
$PM_{2.5}$		0.04		
		[0.01, 0.07]		
		(0.01*)		
		{0.03}		
TVOC			0.05	
			[0.02, 0.08]	
			(< 0.001*)	
			{0.05}	
CO_2				-0.04
				[-0.09, 0]
				(0.04*)
				{0.04}

*Denotes statistical significance for p-value.

From Table 6-1, the model 1 intercept (fixed variables = 0) is at 12.8 (95% CI [6.9, 18.7], $t(5297) = 4.2$, $p < 0.001$). The predicted values from Model 1 showed a significant positive effect of $PM_{2.5}$ (standardised beta = 0.04, $p = 0.01$) on power spectral density (PSD) of delta waveform frequency, with a small effect size. The linear relationship between PSD of delta frequency and $PM_{2.5}$ is shown in Figure 6-5 (A). As the concentration levels of $PM_{2.5}$ increase, high-frequency activity is observed within the delta frequency.

From Table 6-1, the model 2 intercept (fixed variables = 0) is at 12.6 (95% CI [6.7, 18.5], $t(5297) = 4.2$, $p < .001$). The predicted values from Model 2 showed a significant positive effect of TVOC (standardised beta = 0.05, $p < 0.001$) on PSD of delta waveform frequency, with a small effect size. The linear relationship between PSD of delta frequency and TVOC is shown in Figure 6-5 (B). As the concentration levels of TVOC increase, high-frequency activity is observed within the delta frequency.

From Table 6-1, the model 3 intercept (fixed variables = 0) is at 18.9 (95% CI [11.2, 26.5], t (5297) = 4.8, $p < .001$). The increased concentration of CO_2 (Figure 6-5 (C)) saw a decline in PSD unlike $PM_{2.5}$ and TVOC from models 1 and 2, respectively, increases with the intensity of PSD.

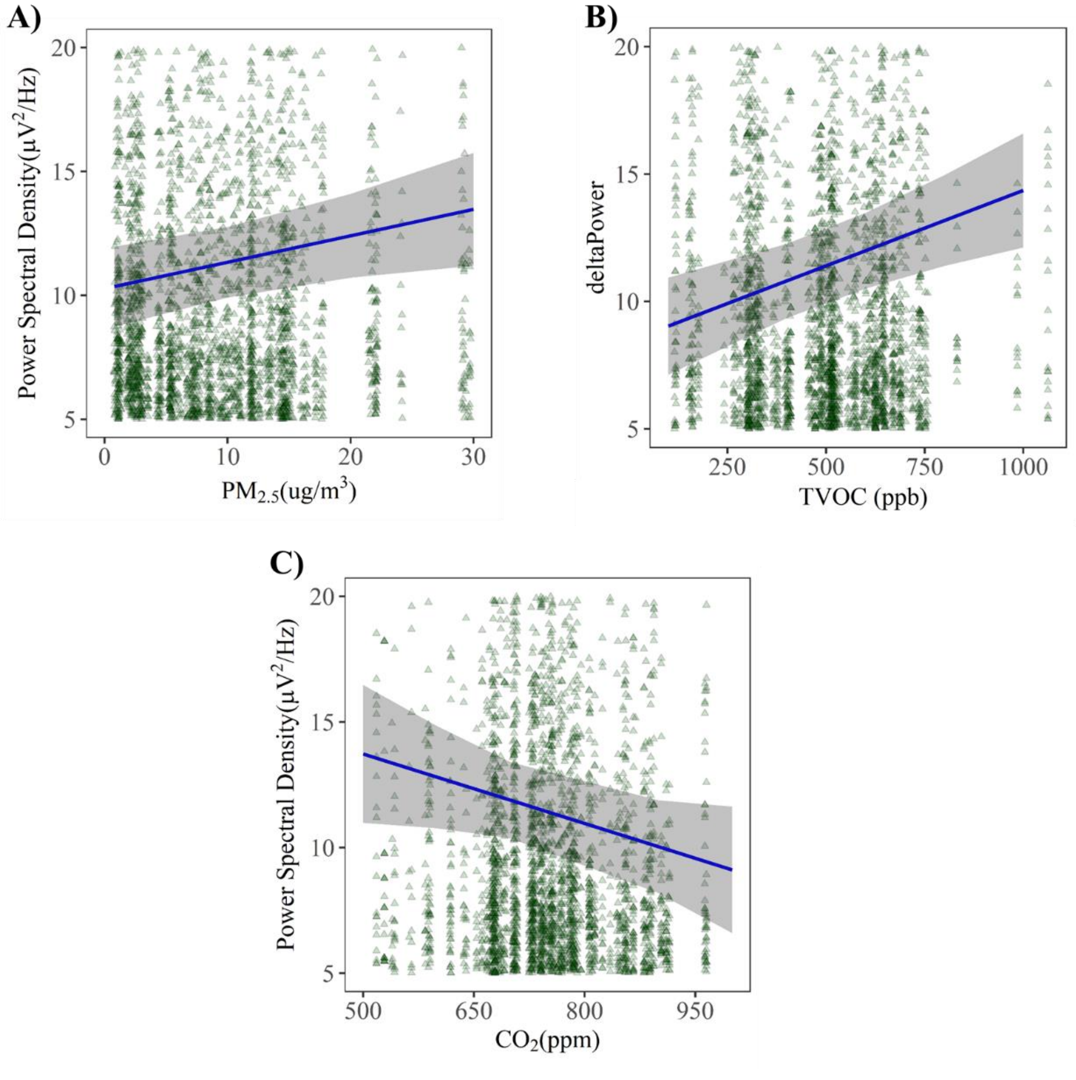


Figure 6-5. Effect of IAQ parameters on delta activity. A) Linear regression line for $PM_{2.5}$ with respect to PSD. B) Linear regression line for TVOC with respect to PSD. C) Linear regression line for CO_2 with respect to PSD. The shaded band represents a confidence interval of 95% of the data. The green triangles represent the data points along the regression line.

6.3.1.1 Delta Rhythm and Brain Regions

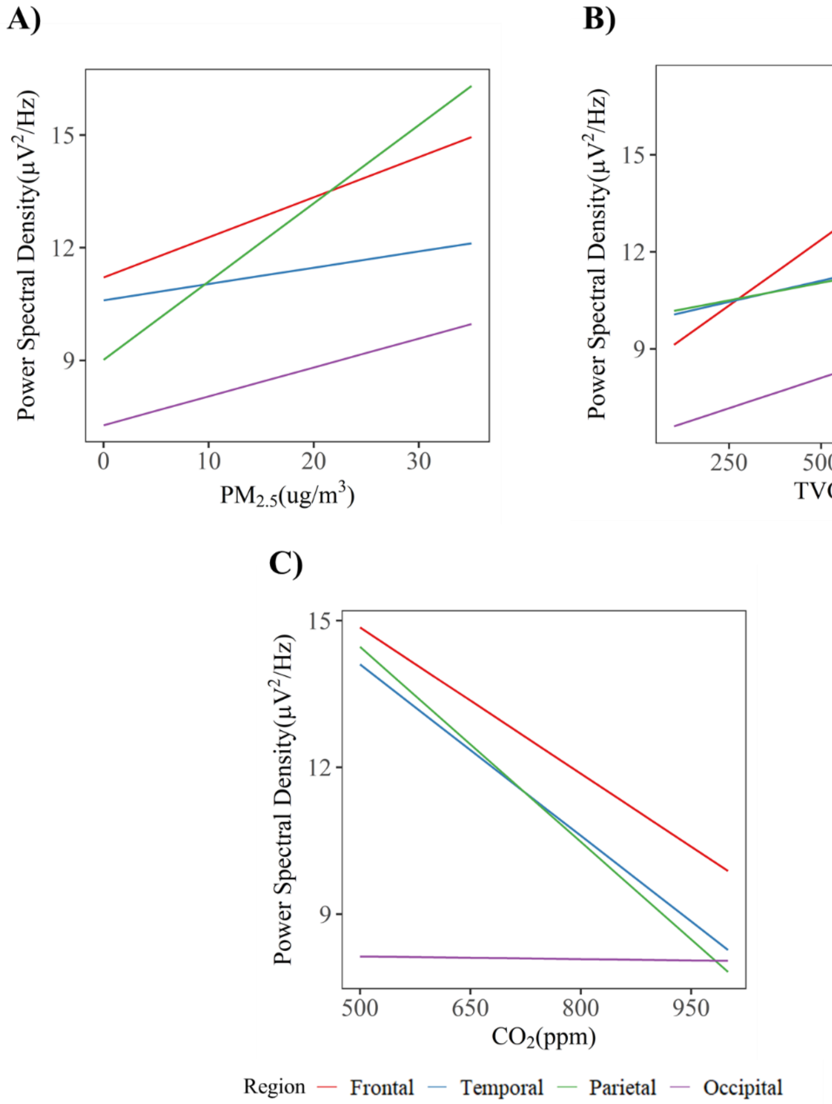


Figure 6-6. Effects of estimated slope for individual brain regions with respect to IAQ parameters and delta activity. A) Linear regression line for $PM_{2.5}$ with respect to PSD. B) Linear regression line for TVOC with respect to PSD. C) Linear regression line for CO_2 with respect to PSD.

Table 0-2. Estimates of slopes of IAQ parameters, $PM_{2.5}$, TVOC, and CO_2 for each of the four brain regions.

	Regions	**Trend**	**Standard Error**	**P-value**
Model 1	Frontal	0.10	0.05	0.04*
	Temporal	0.04	0.09	0.6
	Parietal	0.21	0.09	0.03*
	Occipital	0.07	0.09	0.4
Model 2	Frontal	0.008	0.002	<0.001*
	Temporal	0.002	0.004	0.5
	Parietal	0.002	0.004	0.5
	Occipital	0.003	0.004	0.3

Model 3	Frontal	-0.009	0.005	0.05
	Temporal	-0.01	0.008	0.1
	Parietal	-0.01	0.008	0.1
	Occipital	-0.0001	0.008	0.9

*Denotes statistical significance for p-value.

Comparing Model 1 from Table 6-2 with the different brain regions, the estimated trend in the frontal lobe ($p = 0.04$) and parietal lobe ($p = 0.03$) showed statistical significance. Figure 6-5 (A) shows that the frontal and parietal region's slopes intersect at approximately 20 ug/m^3. When the concentration levels of $PM_{2.5}$ are increased, a higher delta activity is shown in the parietal lobe. When the concentration levels of $PM_{2.5}$ are decreased, a higher delta activity is seen in the frontal lobe. The trend observed from the temporal lobe slope is a gradual increase in the slope gradient compared to frontal and parietal slopes.

Comparing Model 2 from Table 6-2 with the different brain regions, the estimated trend in the frontal lobe ($p < 0.001$) is statistically significant. From Figure 6-6(B), the estimated trend shows an increase in the concentration levels of TVOC, where higher delta activity is seen in the frontal lobe. Parietal and temporal regions' estimated slopes exhibit higher delta activity before intersecting the frontal lobe estimated slope at approximately 250 ppb. However, due to the gradual gradient of the slope, the increase in delta activity is slight. The trend observed from Figure 6-6 for occipital regions slope with respect to $PM_{2.5}$ and TVOC concentration levels, slope gradient, is identical while there is no change seen with respect to CO_2 concentration levels.

6.3.2 Theta Rhythm (4 Hz – 8 Hz)

Table 6-3. Linear regression model testing the effect of IAQ parameters on theta waveform frequency and treating participants as a random intercept. Model parameters: standardised estimate, [95% standard confidence interval], (p-value), and {effect size}.

	Model 0	Model 1	Model 2	Model 3
Scaled Week	-0.001	0.001	-0.001	-0.001
	[-0.03, 0.02]	[-0.03, 0.03]	[-0.03, 0.02]	[-0.04, 0.02]
	(0.58)	(0.92)	(0.69)	(0.6)
	{0}	{0}	{0}	{0}
Fungi	-0.04	0.01	0.01	0.03
	[-0.07, 0]	[-0.02, 0.05]	[-0.02, 0.05]	[-0.01, 0.06]
	(0.02*)	(0.002*)	(0.01*)	(0.02*)

	{0.03}	{0.04}	{0.03}	{0.03}
Bacteria	0.001	0.001	0.001	0.001
	[-0.03, 0.04]	[-0.03, 0.04]	[-0.03, 0.03]	[-0.03, 0.04]
	(0.73)	(0.76)	(0.91)	(0.72)
	{0}	{0}	{0}	{0}
Formaldehyde	0.02	0.02	0.02	0.02
	[-0.01, 0.05]	[-0.01, 0.05]	[-0.01, 0.06]	[-0.01, 0.05]
	(0.2)	(0.21)	(0.17)	(0.2)
	{0.02}	{0.02}	{0.02}	{0.02}
CO	-0.06	-0.06	-0.07	-0.06
	[-0.09, -0.03]	[-0.09, -0.03]	[-0.1, -0.03]	[-0.09, -0.03]
	(< 0.001*)	(< 0.001*)	(< 0.001*)	(< 0.001*)
	{0.06}	{0.05}	{0.06}	{0.05}
$PM_{2.5}$		0.05		
		[0.02, 0.08]		
		(0.001*)		
		{0.05}		
TVOC			0.02	
			[-0.01, 0.05]	
			(0.19)	
			{0.02}	
CO_2				-0.001
				[-0.04, 0.04]
				(0.94)
				{0}

*Denotes statistical significance for p-value.

From Table 6-3, Model 1 intercept (fixed variables = 0) is at 4.7 (95% CI [3.3, 6.1], t (5297) = 6.7, $p < 0.001$). The predicted values from Model 1 showed a significant positive effect of $PM_{2.5}$ (standardised beta = 0.05, p = 0.001) on PSD of theta waveform frequency, with a small effect size. The linear relationship between PSD of theta frequency and $PM_{2.5}$ is shown in Figure 6-7 (A). As the concentration levels of $PM_{2.5}$ increase, high-frequency activity is observed within the theta frequency.

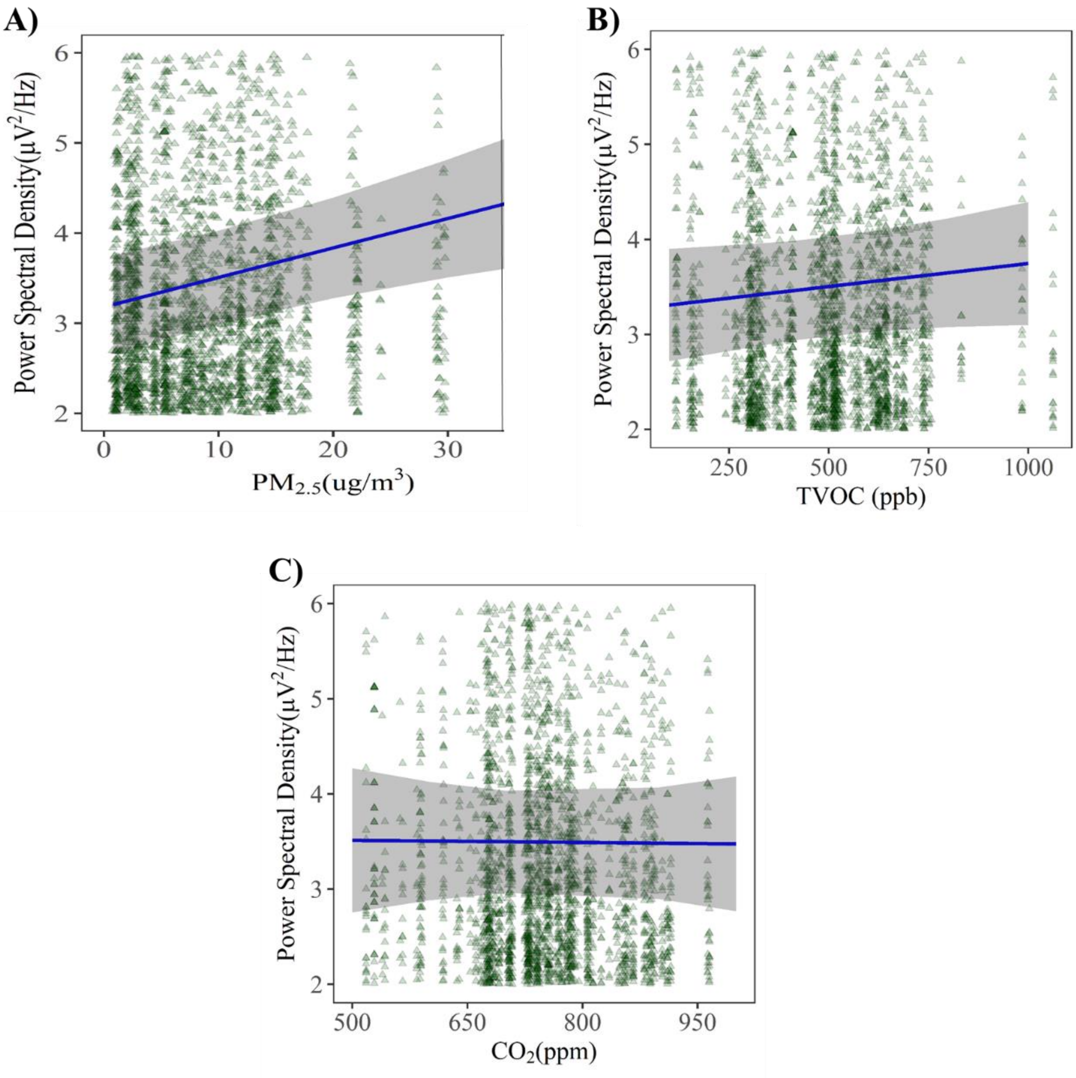


Figure 6-7. Effect of IAQ parameters on theta activity. A) Linear regression line for $PM_{2.5}$ with respect to PSD. B) Linear regression line for TVOC with respect to PSD. C) Linear regression line for CO_2 with respect to PSD. The shaded band represents a confidence interval of 95% of the data. The green triangles represent the data points along the regression line.

6.3.2.1 Theta Rhythm and Brain Regions

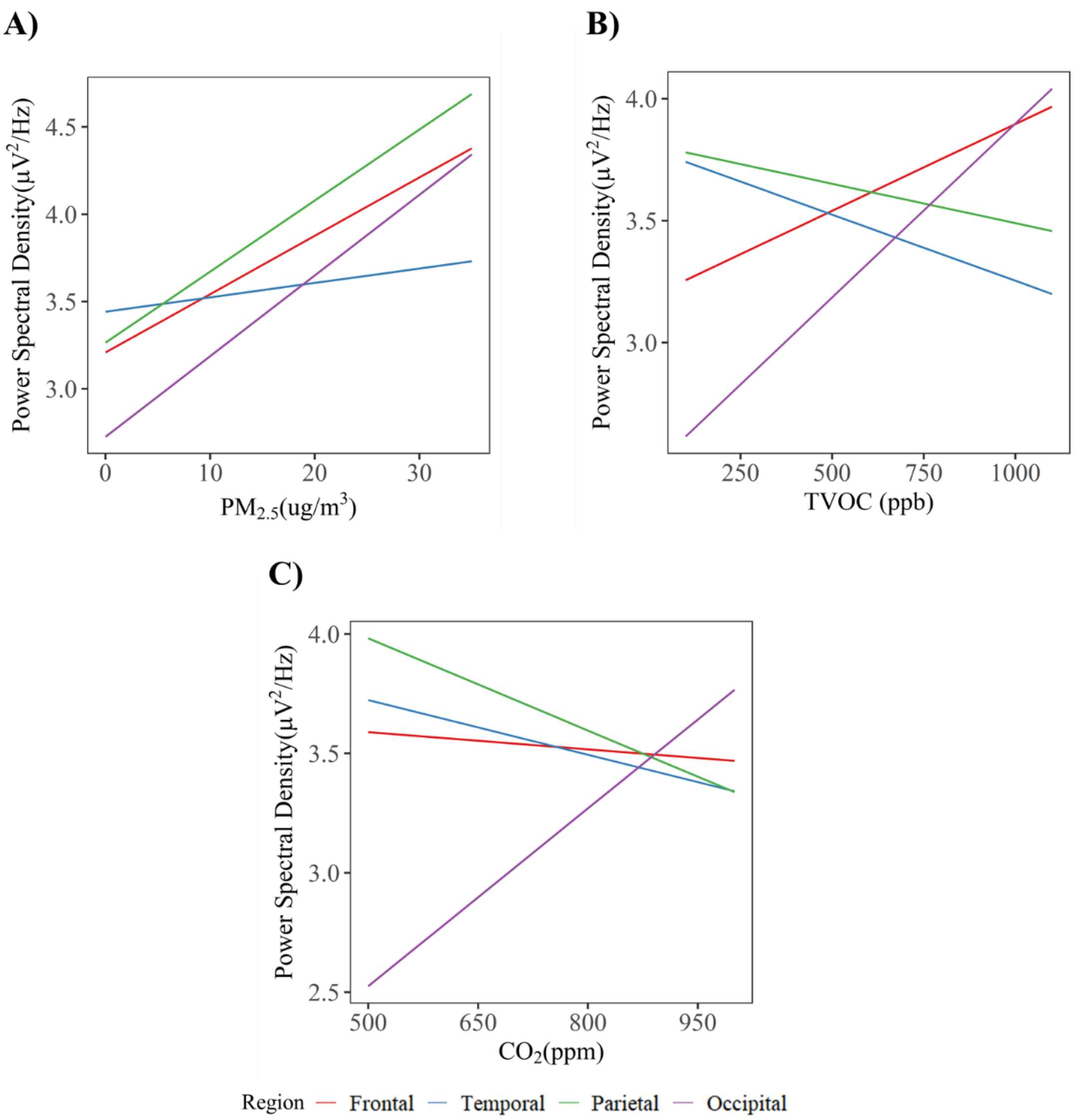


Figure 6-8. Effects of estimated slope for individual brain regions with respect to IAQ parameters and theta activity. A) Linear regression line for $PM_{2.5}$ with respect to PSD. B) Linear regression line for TVOC with respect to PSD. C) Linear regression line for CO_2 with respect to PSD.

Table 6-4. Estimates of slopes of IAQ parameter, $PM_{2.5}$, TVOC, and CO_2 for each of the four brain regions.

	Regions	Trend	Standard Error	P-value
Model 1	Frontal	0.03	0.01	0.005*
	Temporal	0.008	0.02	0.7
	Parietal	0.04	0.02	0.06
	Occipital	0.04	0.02	0.03*
Model 2	Frontal	0.0007	0.0004	0.1
	Temporal	-0.0005	0.0008	0.5
	Parietal	-0.0003	0.0008	0.7
	Occipital	0.001	0.0008	0.1

Model 3	Frontal	-0.0002	0.001	0.8
	Temporal	-0.0007	0.001	0.6
	Parietal	-0.001	0.001	0.4
	Occipital	0.002	0.001	0.1

*Denotes statistical significance for p-value.

Comparing Model 1 from Table 0-4 with the different brain regions, the estimated trend in the frontal lobe (p = 0.04) and occipital lobe (p = 0.03) showed statistical significance. From Figure 6-8 (A), the estimated trend shows an increase in the concentration levels of $PM_{2.5}$, where a high activity in theta frequency is observed in the slopes of the frontal and occipital regions. However, the steep gradient observed in occipital lobe slopes is consistent compared to all three models. An increase in $PM_{2.5}$ and TVOC concentration levels showed an increasing trend in the frontal slopes. Temporal slope with gradual gradient and parietal slope with a steep increasing gradient in Figure 6-8 (A); however, in (B) and (C), both temporal and parietal slopes are observed as a decreasing trend.

6.3.3 Alpha Rhythm (8 Hz – 12 Hz)

Table 6-5. Linear regression model testing the effect of IAQ parameters on alpha waveform frequency and treating participants as a random intercept. Model parameters: standardised estimate, [95% standard confidence interval], (p-value), and {effect size}.

	Model 0	**Model 1**	**Model 2**	**Model 3**
Scaled Week	0.001	0.001	0.001	-0.001
	[-0.02, 0.03]	[-0.02, 0.03]	[-0.03, 0.03]	[-0.04, 0.02]
	(0.84)	(0.53)	(0.97)	(0.62)
	{0}	{0}	{0}	{0}
Fungi	-0.02	-0.03	-0.02	-0.02
	[-0.06, 0.01]	[-0.07, 0]	[-0.05, 0.01]	[-0.06, 0.01]
	(0.11)	(0.03*)	(0.19)	(0.12)
	{0.02}	{0.03}	{0.02}	{0.02}
Bacteria	0.001	0.001	0.001	0.001
	[-0.02, 0.04]	[-0.03, 0.04]	[-0.02, 0.04]	[-0.02, 0.04]
	(0.71)	(0.73)	(0.55)	(0.56)
	{0}	{0}	{0}	{0}
Formaldehyde	-0.001	0.03	0.03	0.04
	[-0.03, 0.02]	[0, 0.07]	[0, 0.06]	[0, 0.07]
	(0.03*)	(0.04*)	(0.04*)	(0.03*)
	{0.03}	{0.03}	{0.03}	{0.03}
CO	0.001	-0.001	-0.001	0.001

	[-0.02, 0.04]	[-0.03, 0.03]	[-0.03, 0.03]	[-0.03, 0.03]
	(0.76)	(0.79)	(0.97)	(0.81)
	{0}	{0}	{0}	{0}
$PM_{2.5}$		0.03		
		[0, 0.06]		
		(0.02*)		
		{0.03}		
TVOC			-0.02	
			[-0.04, 0.01]	
			(0.2)	
			{0.02}	
CO_2				-0.03
				[-0.07, 0.01]
				(0.15)
				{0.02}

*Denotes statistical significance for p-value.

From Table 6-5, the Model 1 intercept (fixed variables = 0) is at 1.33 (95% CI [0.7, 1.8], $t(5297) = 4.7$, $p < 0.001$). The predicted values from Model 1 showed a significant positive effect of $PM_{2.5}$ (standardised beta = 0.03, $p = 0.02$) on PSD of alpha waveform frequency, with a small effect size. The linear relationship between PSD of alpha frequency and $PM_{2.5}$ is shown in Figure 6-9 (A). As the concentration levels of $PM_{2.5}$ increase, high-frequency activity is observed within the alpha frequency. For Models 2 and 3, in Figure 6-9 (B) and (C), there is a decreasing trend of alpha activity when the concentration levels of TVOC and CO_2 are high.

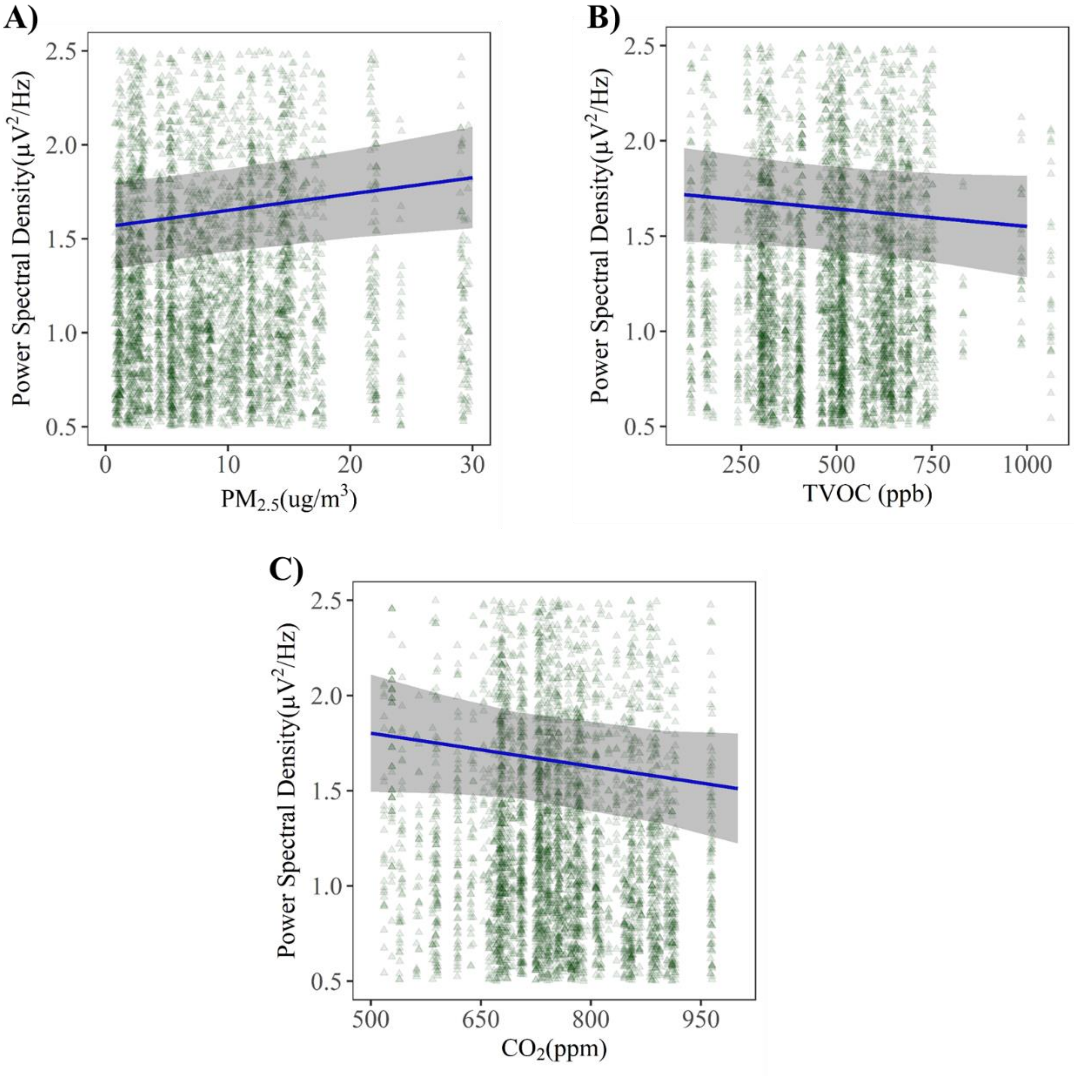


Figure 6-9. Effect of IAQ parameters on alpha activity. A) Linear regression line for $PM_{2.5}$ with respect to PSD. B) Linear regression line for TVOC with respect to PSD. C) Linear regression line for CO_2 with respect to PSD. The shaded band represents a confidence interval of 95% of the data. The green triangles represent the data points along the regression line.

6.3.3.1 Alpha Rhythm and Brain Regions

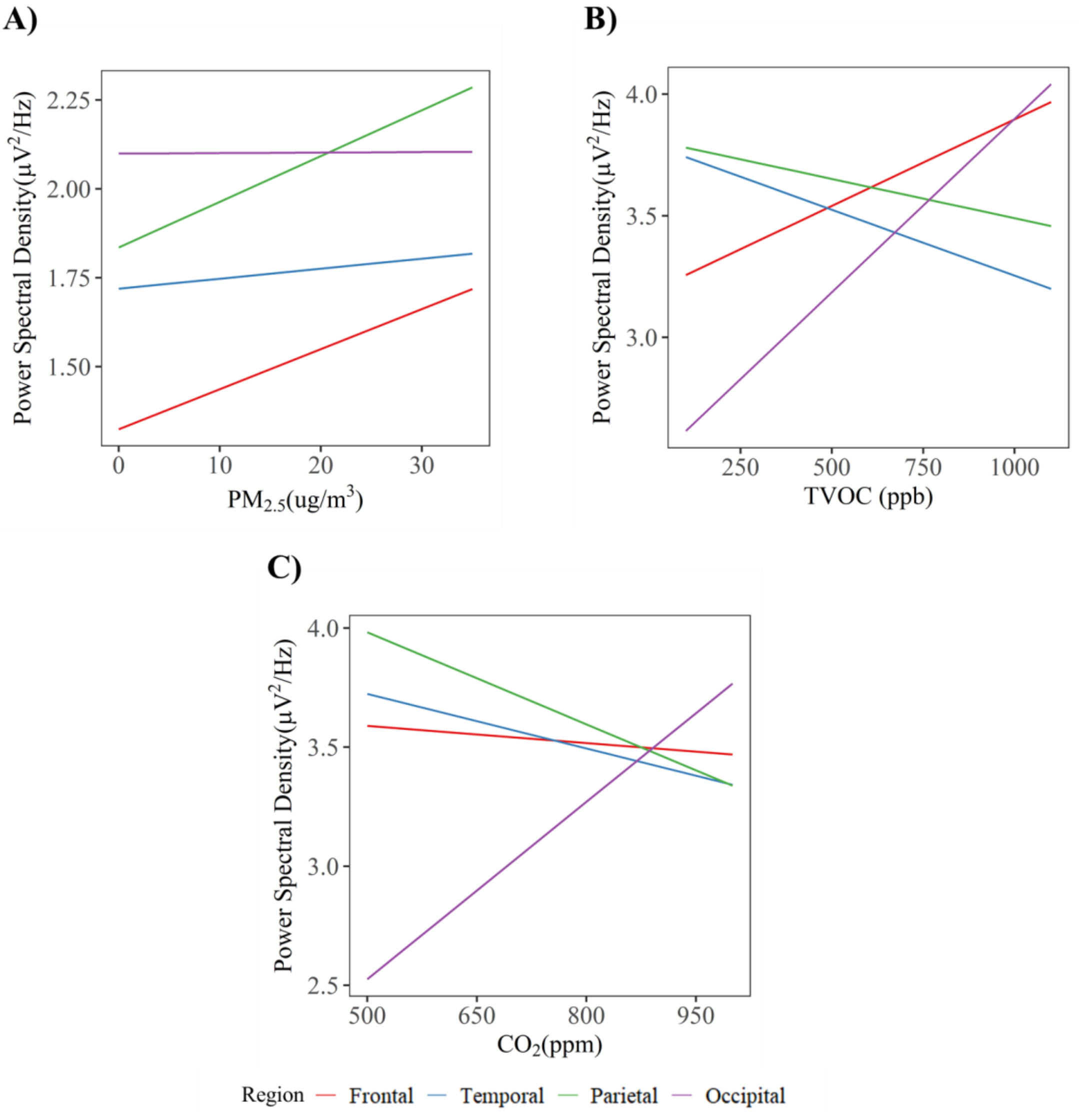


Figure 6-10. Effects of estimated slope for individual brain regions with respect to IAQ parameters and delta activity. A) Linear regression line for $PM_{2.5}$ with respect to PSD. B) Linear regression line for TVOC with respect to PSD. C) Linear regression line for CO_2 with respect to PSD.

Table 0-6. Estimates of slopes of IAQ parameter, $PM_{2.5}$, TVOC, and CO_2 for each of the four brain regions.

	Regions	Trend	Standard Error	P-value
Model 1	Frontal	0.01	0.004	0.01*
	Temporal	0.002	0.008	0.7
	Parietal	0.01	0.008	0.1
	Occipital	0.0001	0.008	0.9
Model 2	Frontal	0.0007	0.0004	0.1
	Temporal	-0.0005	0.0008	0.5
	Parietal	-0.0003	0.0008	0.7

	Occipital	0.001	0.0008	0.1
Model 3	Frontal	-0.0002	0.001	0.8
	Temporal	-0.0007	0.001	0.6
	Parietal	-0.001	0.001	0.4
	Occipital	0.002	0.001	0.1

*Denotes statistical significance for p-value.

Comparing Model 1 from Table 6-6 with the different brain regions, the estimated trend in the frontal lobe (p = 0.01) showed statistical significance. From Figures 6-10 (A), the estimated trend shows an increase in the concentration levels of $PM_{2.5}$, where a high activity within alpha frequency is observed in the frontal regions. The same trend is observed in the parietal lobe slope, while alpha activity at temporal and occipital regions shows a consistent trend across $PM_{2.5}$ with increasing concentration levels. Figures 6-10 (B) and (C) show that parietal and temporal slopes are negative. An increase in TVOC and CO_2 concentration levels is seen with decreased alpha activity. The alpha activity at the frontal lobe is not affected by the increasing concentration levels of CO_2, but an increasing trend is observed with the increasing concentration levels of TVOC.

6.3.4 Beta Rhythm (12 Hz – 30 Hz)

Table 6-7. Linear regression model testing the effect of IAQ parameters on beta waveform frequency and treating participants as a random intercept. Model parameters: standardised estimate, [95% standard confidence interval], (p-value), and {effect size}.

	Model 0	Model 1	Model 2	Model 3
Scaled Week	-0.07	-0.07	-0.07	-0.07
	[-0.1, -0.05]	[-0.1, -0.05]	[-0.1, -0.04]	[-0.09, -0.03]
	(< 0.001*)	(< 0.001*)	(< 0.001*)	(< 0.001*)
	{0.07}	{0.07}	{0.07}	{0.05}
Fungi	0.02	0.02	-0.02	-0.02
	[-0.01, 0.05]	[-0.01, 0.06]	[-0.05, 0.01]	[-0.06, 0.01]
	(0.21)	(0.2)	(0.26)	(0.24)
	{0.02}	{0.02}	{0.02}	{0.02}
Bacteria	-0.01	-0.01	-0.01	-0.01
	[-0.04, 0.02]	[-0.04, 0.02]	[-0.05, 0.02]	[-0.05, 0.02]
	(0.44)	(0.44)	(0.38)	(0.32)
	{0.01}	{0.01}	{0.01}	{0.01}
Formaldehyde	-0.001	-0.02	-0.03	-0.02
	[-0.03, 0.02]	[-0.05, 0.02]	[-0.05, 0.02]	[-0.05, 0.02]
	(0.29)	(0.29)	(0.31)	(0.28)

	{0.02}	{0.02}	{0.02}	{0.02}
CO	0.02	0.02	0.02	0.02
	[-0.01, 0.05]	[-0.01, 0.05]	[-0.01, 0.05]	[-0.03, 0.03]
	(0.16)	(0.16)	(0.21)	(0.46)
	{0.02}	{0.02}	{0.02}	{0.01}
$PM_{2.5}$		0.03		
		[0, 0.06]		
		(0.77)		
		{0}		
TVOC			-0.02	
			[-0.04, 0.01]	
			(0.54)	
			{0}	
CO_2				-0.03
				[-0.07, 0.01]
				(0.12)
				{0.03}
AIC	22415.1	22426.0	22432.2	22428.2
ΔAIC	0	10.8	13.1	17.1
AIC Weightage	99.4%	0.5%	0.1%	0%

*Denotes statistical significance for p-value.

Table 6-7 shows that the IAQ parameters in Models 1, 2, and 3 did not show statistical significance. Thus, no further analysis was carried out for beta frequency.

6.3.5 Engagement Indices

The calculation of the engagement indices is based on alpha, beta, and theta rhythm activity and the specific brain regions. Refer to section 6.2.4 for the formulas used to obtain the engagement indices.

6.3.5.1 Engagement Index 1

Table 6-8. Linear regression model tests the effect of IAQ parameters on engagement index 1 and treats participants as a random intercept. Model parameters: standardised estimate, [95% standard confidence interval], (p-value), and {effect size}.

	Model 0	Model 1	Model 2	Model 3
Scaled Week	-0.09	-0.10	-0.09	-0.07
	[-0.12, -0.06]	[-0.13, -0.07]	[-0.12, -0.06]	[-0.1, -0.04]
	(< 0.001*)	(< 0.001*)	(< 0.001*)	(< 0.001*)
	{0.09}	{0.1}	{0.09}	{0.06}
Fungi	0.04	0.05	0.04	0.04
	[0.01, 0.07]	[0.02, 0.09]	[0.01, 0.07]	[0.01, 0.07]

	(0.01*)	(0.002*)	(0.02*)	(0.01*)
	{0.04}	{0.04}	{0.03}	{0.03}
Bacteria	0.02	0.02	0.02	0.02
	[-0.01, 0.05]	[-0.01, 0.05]	[-0.01, 0.05]	[-0.02, 0.05]
	(0.17)	(0.16)	(0.24)	(0.32)
	{0.02}	{0.02}	{0.02}	{0.01}
Formaldehyde	-0.001	-0.001	-0.001	-0.001
	[-0.04, 0.03]	[-0.04, 0.03]	[-0.04, 0.03]	[-0.04, 0.03]
	(0)	(0.72)	(0.76)	(0.66)
	{0.02}	{0}	{0}	{0}
CO	0.02	0.02	0.01	0.001
	[-0.01, 0.05]	[-0.01, 0.05]	[-0.02, 0.05]	[-0.03, 0.03]
	(0.24)	(0.25)	(0.34)	(0.88)
	{0.02}	{0.02}	{0.01}	{0}
$PM_{2.5}$		-0.04		
		[-0.07, -0.01]		
		(0.01*)		
		{0.03}		
TVOC			0.01	
			[-0.01, 0.04]	
			(0.35)	
			{0.01}	
CO_2				0.05
				[0.01, 0.09]
				(0.01*)
				{0.04}

*Denotes statistical significance for p-value.

From Table 6-8, Model 1 intercept (fixed variables = 0) is at 0.14 (95% CI [0.07, 0.21], t (5297) = 4.8, $p < 0.001$). The Model 3 intercept (fixed variables = 0) is at 0.05 (95% CI [-0.04, 0.15], t (5297) = 1.1, p = 0.2). The predicted values from Model 1 showed a significant negative effect of $PM_{2.5}$ (standardised beta = -0.04, p = 0.01) with a small effect size. The predicted values from Model 3 showed a significant positive effect of CO_2 (standardised beta = 0.05, p = 0.01) with a small effect size.

For Model 1, as concentration levels of $PM_{2.5}$ increase, the engagement index 1 ratio decreases. This would suggest that high concentration levels of $PM_{2.5}$ reduce attention to the tasks, as shown in Figure 6-11(A). In contrast, for Model 3, as concentration levels of CO_2 increase, the engagement index 1 ratio increases. Indicating that there is higher engagement at high concentration levels of CO_2, as shown in Figure 6-11(C). The CO_2 effect indicated in Model 3 could be the effect of bio-effluent fungi (p=0.01).

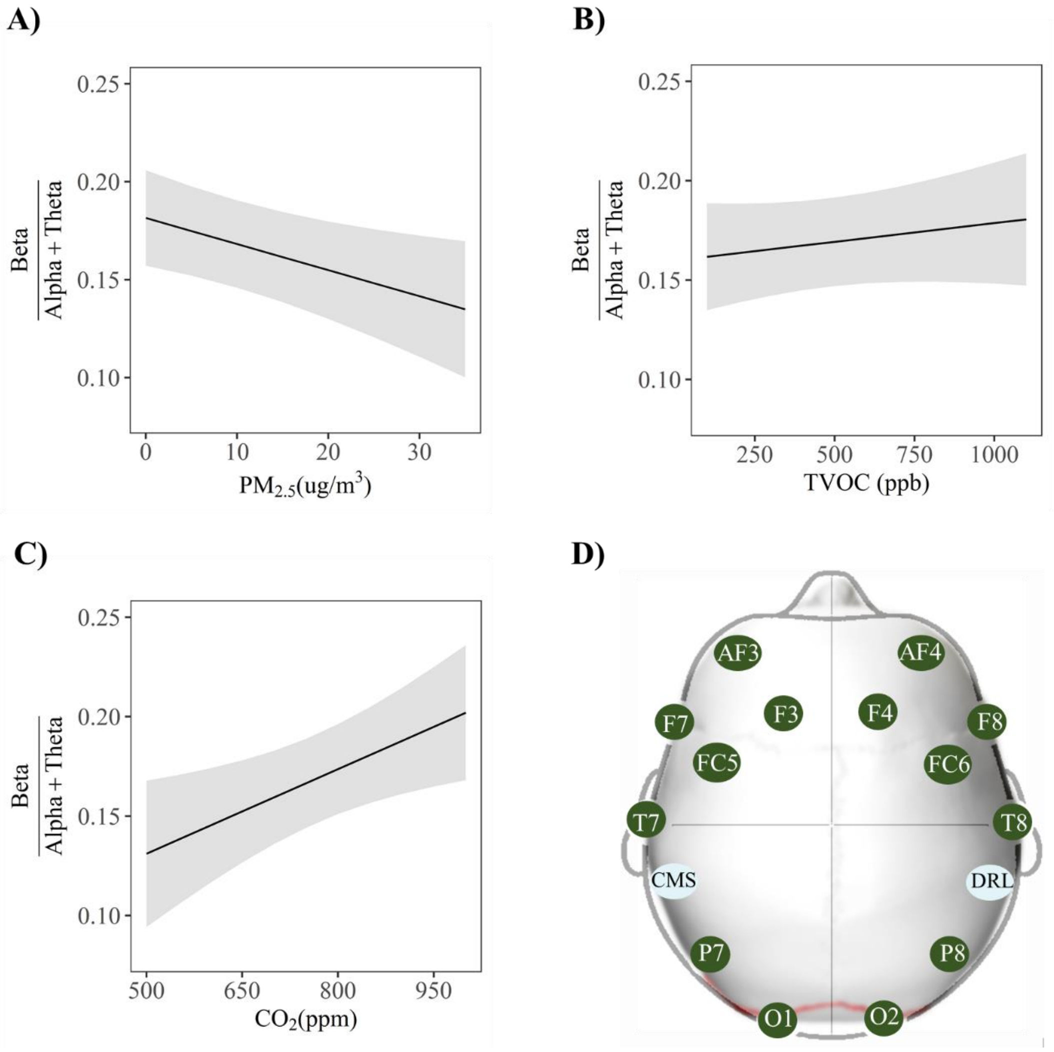


Figure 6-11. Effects of IAQ parameters on Index 1**.** A) Linear regression line for $PM_{2.5}$ with respect to Index 1. B) Linear regression line for TVOC with respect to Index 1. C) Linear regression line for CO_2 with respect to Index 1. D) The selected electrodes were used in the engagement index calculation, averaging across the 14 electrodes.

6.3.5.2 Engagement Index 2

Table 6-9. Linear regression model tests the effect of IAQ parameters on engagement index 2 and treats participants as a random intercept. Model parameters: standardised estimate, [95% standard confidence interval], (p-value), and {effect size}.

	Model 0	**Model 1**	**Model 2**	**Model 3**
Scaled Week	0.01	0.001	0.01	0.03
	[-0.01, 0.04]	[-0.02, 0.03]	[-0.01, 0.04]	[0, 0.06]
	(0.32)	(0.62)	(< 0.001*)	(< 0.001*)
	{0.01}	{0}	{0.01}	{0.03}
Fungi	-0.04	-0.03	-0.04	-0.04
	[-0.07, -0.02]	[-0.06, 0]	[-0.07, -0.02]	[-0.07, -0.02]
	(0.002*)	(0.02*)	(0.002*)	(0.002*)
	{0.04}	{0.03}	{0.04}	{0.04}

Bacteria	0.06	0.06	0.06	0.06
	[0.04, 0.09]	[0.04, 0.09]	[0.04, 0.09]	[0.03, 0.09]
	(< 0.001*)	(< 0.001*)	(< 0.001*)	(< 0.001*)
	{0.06}	{0.06}	{0.06}	{0.06}
Formaldehyde	0.001	0.001	0.001	0.001
	[-0.02, 0.04]	[-0.02, 0.04]	[-0.02, 0.04]	[-0.02, 0.04]
	(0.58)	(0.55)	(0.56)	(0.68)
	{0.02}	{0}	{0}	{0}
CO	-0.02	-0.02	-0.02	-0.04
	[-0.05, 0]	[-0.05, 0]	[-0.05, 0]	[-0.06, -0.01]
	(0.11)	(0.02)	(0.10)	(0.01*)
	{0.02}	{0.02}	{0.02}	{0.03}
$PM_{2.5}$		-0.03		
		[-0.06, -0.01]		
		(0.01*)		
		{0.03}		
TVOC			0.001	
			[-0.02, 0.03]	
			(0.69)	
			{0}	
CO_2				0.05
				[0.02, 0.09]
				(0.005*)
				{0.04}

*Denotes statistical significance for p-value.

From Table 6-9, Model 1 intercept (fixed variables = 0) is at 2.13 (95% CI [1.68, 2.58], $t(5297) = 9.2$, $p < 0.001$). The Model 3 intercept (fixed variables = 0) is at 1.56 (95% CI [0.99, 2.14], $t(5297) = 5.38$, $p < 0.001$). The predicted values from Model 1 showed a significant negative effect of $PM_{2.5}$ (standardised beta = -0.03, p = 0.01) with a small effect size. The predicted values from Model 3 showed a significant positive effect of CO_2 (standardised beta = 0.05, p = 0.005) with a small effect size.

For Model 1, an increase in concentration levels of $PM_{2.5}$ is associated with a low engagement index 2 ratio and less mental stress, as shown in Figure 6-12(A). In contrast, for Model 3, an increase in CO_2 is associated with a high engagement index 2 ratio reflecting high mental stress, as shown in Figure 6-12 (C). Model 2, in Figure 6-12 (B), shows a similar trend to Model 3 with a gradual increase in the engagement index 2 ratio.

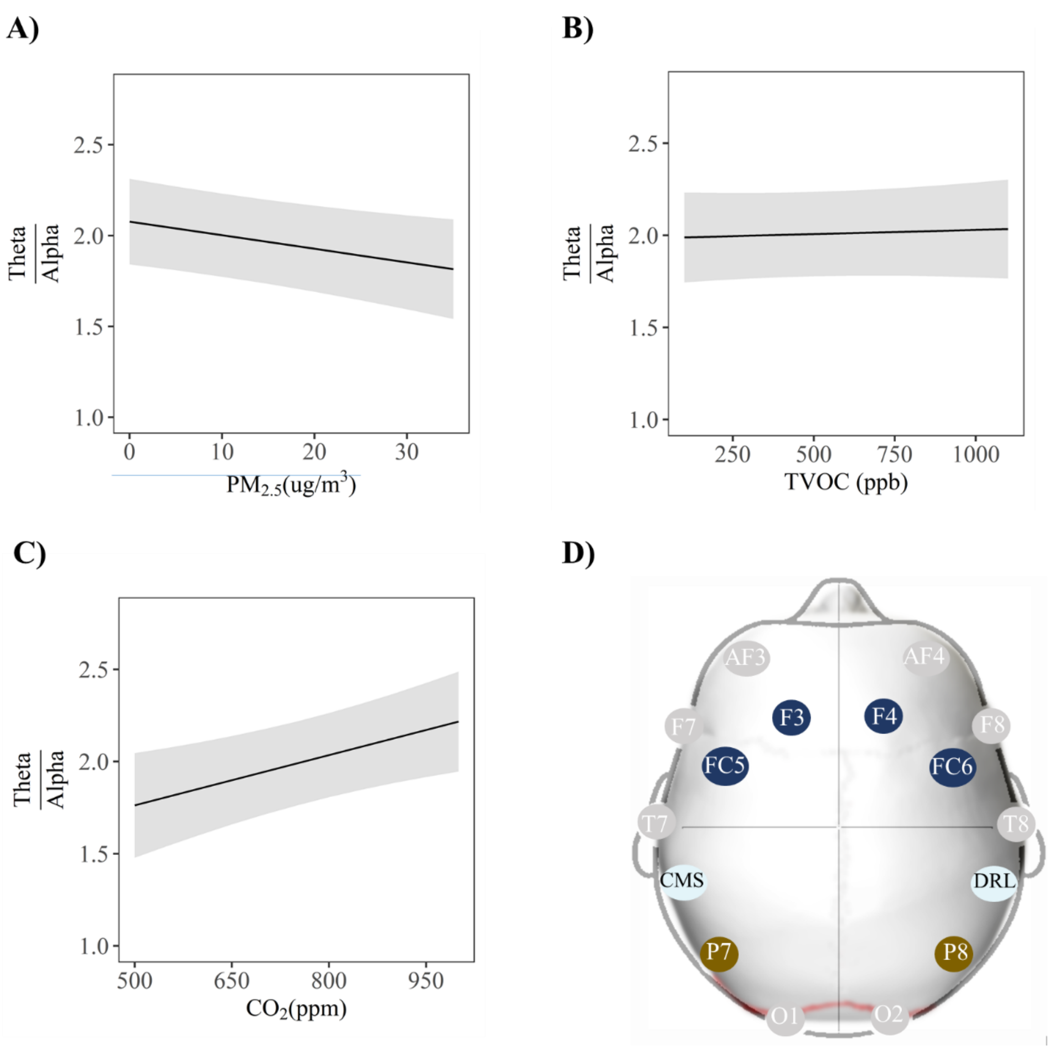


Figure 6-12. Effects of IAQ parameters on Index 2. A) Linear regression line for $PM_{2.5}$ with respect to Index 2. B) Linear regression line for TVOC with respect to Index 2. C) Linear regression line for CO_2 with respect to Index 2. D) The selected electrodes are used in the engagement index calculation.

6.3.5.3 Engagement Index 3

Table 6-10. Linear regression model tests the effect of IAQ parameters on engagement index 3 and treats participants as a random intercept. Model parameters: standardised estimate, [95% standard confidence interval], (p-value), and {effect size}.

	Model 0	Model 1	Model 2	Model 3
Scaled Week	-0.01	0.001	-0.001	-0.001
	[-0.04, 0.01]	[-0.02, 0.03]	[-0.03, 0.01]	[-0.03, 0.02]
	(0.19)	(0.75)	(0.41)	(0.74)
	{0.02}	{0}	{0.01}	{0}
Fungi	-0.07	-0.1	-0.08	-0.07
	[-0.09, -0.04]	[-0.13, -0.07]	[-0.1, -0.05]	[-0.09, -0.04]
	(< 0.001*)	(< 0.001*)	(< 0.001*)	(< 0.001*)
	{0.07}	{0.1}	{0.08}	{0.07}

Bacteria	0.03	0.03	0.02	0.03
	[0.01, 0.06]	[0, 0.06]	[0, 0.05]	[0, 0.06]
	(0.01*)	(0.02*)	(0.09)	(0.03*)
	{0.03}	{0.03}	{0.02}	{0.03}
Formaldehyde	0.05	0.05	0.05	0.05
	[0.02, 0.08]	[0.02, 0.07]	[0.02, 0.08]	[0.02, 0.07]
	(< 0.001*)	(0.002*)	(< 0.001*)	(0.001*)
	{0.05}	{0.04}	{0.05}	{0.04}
CO	-0.07	-0.07	-0.08	-0.08
	[-0.1, -0.05]	[-0.1, -0.05]	[-0.11, -0.06]	[-0.11, -0.06]
	(< 0.001*)	(< 0.001*)	(< 0.001*)	(< 0.001*)
	{0.08}	{0.08}	{0.09}	{0.08}
$PM_{2.5}$		0.11		
		[0.08, 0.13]		
		(< 0.001*)		
		{0.12}		
TVOC			0.04	
			[0.02, 0.07]	
			(< 0.001*)	
			{0.05}	
CO_2				0.03
				[0, 0.07]
				(0.08)
				{0.02}

*Denotes statistical significance for p-value.

From Table 6-10, Model 1 intercept (fixed variables = 0) is at 3.95 (95% CI [3.08, 4.81], t (5297) = 8.9, $p < 0.001$). The predicted values from Model 1 showed a significant positive effect of $PM_{2.5}$ (standardised beta = 0.11, $p < 0.001$) with a small effect size. The Model 2 intercept (fixed variables = 0) is at 4.19 (95% CI [3.32, 5.05], t (5297) = 9.5, $p < 0.001$). The predicted values from Model 2 showed a significant positive effect of TVOC (standardised beta = 0.04, $p < 0.001$) with a small effect size.

Engagement index 3 reflects the engagement of mental effort. According to Smit et al. (2005), a high engagement index 3 average means increased mental effort. That translates to a high attention and alertness. For Model 1, an increase in concentration levels of $PM_{2.5}$ is associated with a high engagement index 3 average and low alertness, as shown in Figure 6-13 (A). Models 2 and 3, in Figures 6-13 (B) and (C), respectively, show similar trends as Model 1.

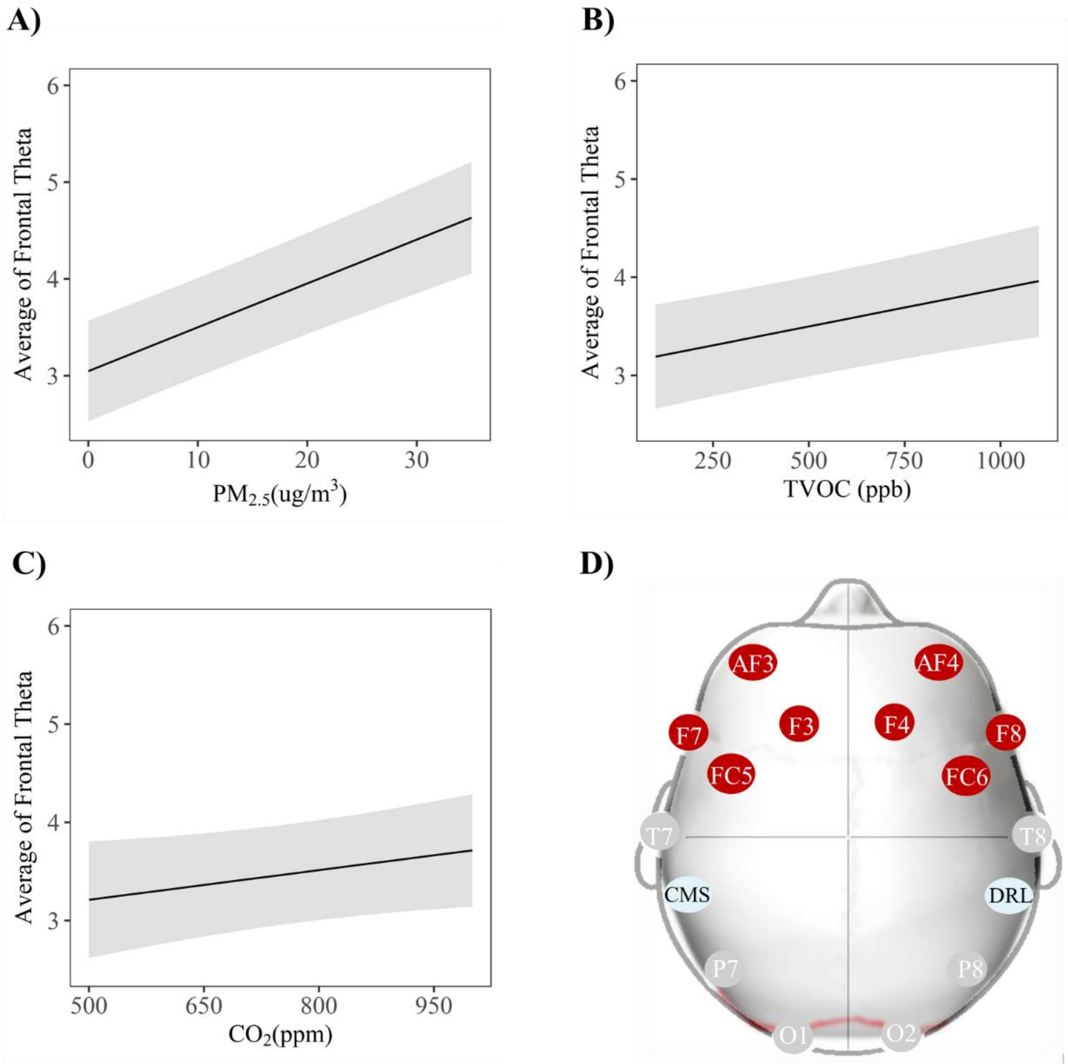


Figure 6-13. Effects of IAQ parameters on Index 3. A) Linear regression line for $PM_{2.5}$ with respect to Index 3. B) Linear regression line for TVOC with respect to Index 3. C) Linear regression line for CO_2 with respect to Index 3. D) The selected electrodes are used in the engagement index calculation.

6.4 Discussion

The study investigated the possible association between common IAQ pollutants, $PM_{2.5}$, TVOC, and CO_2 (bio-effluents) and electrophysiological responses using a PEBL test battery as a stimulant to test the cognitive abilities of young adults over 6 weeks of varying IAQ conditions. Participants were reminded not to disengage with the task. This ensured that the level of difficulty (load) experienced was consistent. Table 6-11 summarises the significant results from the previous section, and Table 6-12 summarises the results from the stimulus.

Table 6-11. Summary of the engagement indices and its significant IAQ parameter ($p<0.05$).

Ratio	Formula (power)	Association	*$PM_{2.5}$	*TVOC	*CO_2
EI 1	$\frac{\text{Beta}}{\text{Alpha + Theta}}$	Mental workload	Decrease	-	Increase
EI 2	$\frac{\text{Frontal Theta}}{\text{Parietal Alpha}}$	Task load	Decrease	-	Increase
EI 3	Average Frontal Theta	Mental effort	Increase	Increase	-

Note: * indicates increased IAQ parameters concentration levels; EI - indicates engagement index.

Table 6-12. Summary of PEBL task administered as a stimulus. Only statistically significant ($p < 0.05$) results are presented.

Cognitive Task	Cognitive function	$PM_{2.5}$	TVOC	CO_2	Measurement
Operation Span	Working memory	-	X	-	RT
Sternberg Scanning	Working memory	X	-	-	RT
BCST	Cognitive flexibility & control	-	X	-	RT
TOL	Planning	-	-	X	Success
Time-wall	Cognitive flexibility & control	-	X	-	Accuracy in terms of RT
Mental Rotation	Fluid intelligence	-	X	-	RT

RT – indicates reaction time, X – indicates a significant result

High concentration levels of $PM_{2.5}$ are associated with a low engagement index 1. A low mental workload suggests a lack of motivation for the task demand and the possibility of being associated with higher errors. The Csikszentmihalyi (1997) flow theory describes full engagement when the flow is attained at high efficacy and high arousal (See Figure 6-14). According to the flow model, lack of motivation occurs when an overmatch or underutilised arousal and efficacy occurs.

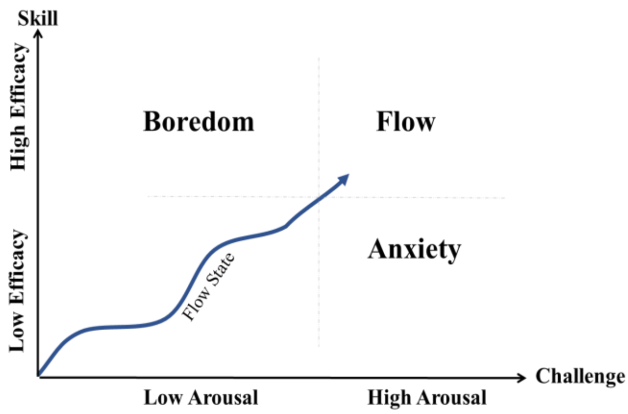


Figure 6-14. Model of flow theory. Adapted from (Csikszentmihalyi, 1997).

- $PM_{2.5}$

Examining the alpha band activity and theta band activity across all electrodes (refer to Figures 6-6 and 6-8 (A)), the sum of alpha and theta activities at high concentration levels of $PM_{2.5}$ possibly reflects fatigue due to drowsiness (Rabbi et al., 2012). Beta band activity is assumed to have no changes due to statistical insignificance in the concentration levels of $PM_{2.5}$. Thus, an increase in fatigue implies low efficacy. The motivational control model (Hockey, 2013) considers environmental factors ($PM_{2.5}$) as stressors that can disrupt goal maintenance. According to the model, the effect of $PM_{2.5}$ increases mental fatigue, which needs to be compensated by increasing the goal-directed mental effort. This is observed in engagement index 2, where a low task load is reported at high concentration levels of $PM_{2.5.}$ The low task load ratio in engagement index 2 relates to an increase in mental fatigue due to the increasing trend observed in the partial alpha-band activity (Figure 6-9 (A))(Smith & Gevins, 2005). The increase in mental effort is observed in engagement index 3 where high mental effort is reported at high concentration levels of $PM_{2.5}$. Therefore, interpreting all 3 engagement indices at high concentration levels of $PM_{2.5,}$ there is high mental fatigue, and participants must increase mental effort to maintain the goal of the task. This, according to the flow model (Figure 0-14), causes high arousal (increase in mental effort) at low efficacy (high mental fatigue), which indicates anxiety.

Analysing the engagement index 3 ratio, indicates that frontal theta-band activity is associated with increased mental effort from the participants. Previous studies have reported that high frontal theta activity increases the memory load in working memory (Itthipuripat et al., 2013; Jensen & Tesche, 2002). Toxicology studies with rats showed that exposure to $PM_{2.5}$ impaired memory inquiring ability (Ning et al., 2018; Q. Zhang et al., 2018). Based on Table 6-12, examining the cognitive tasks administered as a stimulus, exposure to $PM_{2.5}$ showed statistical significance in working memory. Working memory is affected by anxiety and stress (Hoeger Bement et al., 2010), and from the current study, high concentration levels of $PM_{2.5}$ indicated anxiety. Cognitive stress could be built upon anxiety, and in a recent study, it is shown to impair working memory in young adults (18-30 years) (Fabio et al., 2021).

Further examining the biological impact due to cognitive stress had indicated the loss of neurons in the hippocampus (McEwen & Sapolsky, 1995). Several studies have reported the changes observed in the hippocampal neuron due to $PM_{2.5}$ exposure (Tesche & Karhu, 2000) affected the working memory mainly in rodents, and further human study is required to confirm the biological pathway (Chao et al., 2017; Q. Li et al., 2018; Motesaddi Zarandi et al., 2019; Ning et al., 2018; Yang et al., 2017). In addition, the pathway of the spread of $PM_{2.5}$ deposited at the olfactory to the hippocampus requires further research. This study showed that high concentration levels of $PM_{2.5}$ in the indoor environment cause cognitive stress (mental fatigue), which introduces anxiety and leads to occupants exerting more mental effort to perform, which has been reflected to affect working memory.

- TVOC

High concentration levels of TVOC, as shown in Table 6-11, are associated with a high engagement index 3 ratio. The increase in frontal theta-band activity (refer to Figures 6-7 (B)) translates to high mental effort. According to the motivational control model (Hockey, 2013), the environmental stressor, TVOC increases, and the task performance is expected to decrease. This effect is countered by increasing mental effort. Therefore, an increase in TVOC concentration levels increases the engagement index 3 ratio indicating high mental effort.

TVOC is observed to affect various cognitive functions. Among the different tasks shown in Table 6-12, TVOC influences the reaction time. Hence the mental fatigue caused by high concentration levels of TVOC (stressor) is compensated by increasing mental effort (reaction time). As stated previously, an increase in frontal theta-band activity is shown to increase memory load, which affects the working memory (Jensen

& Tesche, 2002). Examining further into the individual chemical components of TVOC, (GCMS analysis) from this study showed high concentrations in ethylbenzene, styrene, and toluene with a match score of more than 99.0 (see Figure 0-15). Among these 3 VOCs listed, styrene has been reported to affect cognitive functions in literature.

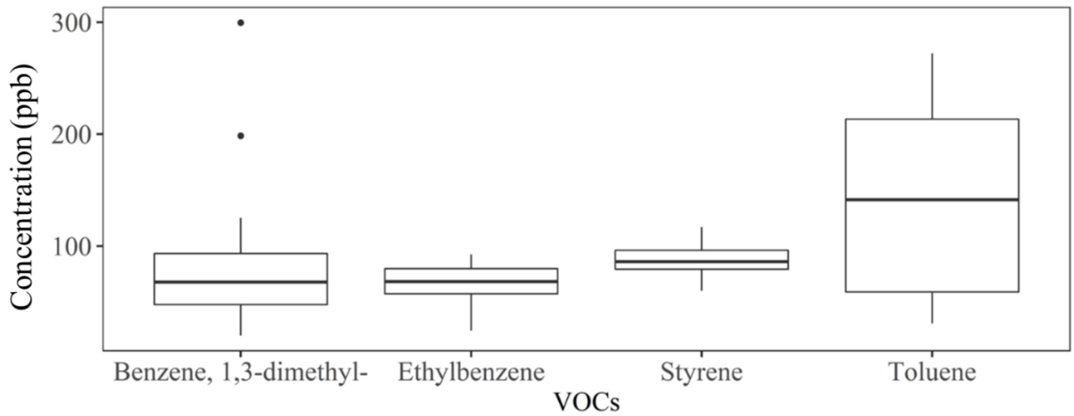


Figure 6-15. Identification of VOCs with the highest concentration from GCMS analysis. Only VOCs with a match score of 99.0 – 99.9 were identified using the NIST library computed across all rounds and conditions. Among those identified, 4 compounds showed high levels of concentration.

Being exposed to styrene has been well documented, indicating poor memory, slow response speed, and reduced vigilance (Anger, 1990). A study on 30 young adults being exposed for 5 days and 8 hours per day for a week concludes that exposure to styrene to more than 26 ppb would delay reaction time and more than 50 ppb for short memory (Mutti et al., 1984). Thus, to compensate for the fatigue induced by TVOC to maintain performance (goal) in the given task has been reflected in the delay in reaction time (increased mental effort). Since there is no statistical significance observed in engagement indexes 1 and 2 with high concentration levels of TVOC, we do not have any information to deduce if high concentration levels of TVOC could cause anxiety.

- CO_2

High concentration levels of CO_2 are shown (Table 6-11) to be associated with a high engagement index 1 (mental workload) and 2 (task load). It suggests that high engagement in the task is at the expense of high effort. A high engagement index 2 could be translated as the task being perceived as complex than it originally was. From the motivational control model, to meet the task demand, the increase in stress caused by high concentration levels of CO_2 (engagement index 1) evokes a different degree of engagement. In agreement, X. Zhang, Wargocki, & Lian (2017) indicated in their study that 25 participants exposed to 4 hours and 25 minutes of increasing concentration levels of CO_2 observed high arousal or stress through physiological responses. The increase in stress or arousal reflects an effect observed in planning (see Table 6-12). Since the current study had used CO_2 as a proxy of bio-effluents generated by the participants, the effects observed in CO_2 could reflect the influences from other IAQ pollutants. Examination of the individual wave band activities (alpha, theta, and beta), theta-band activity (see Table 6-4) showed statistical significance in fungi count level and carbon monoxide under Model 3. The fungi count level, a possible bio-effluent, has been shown to increase when concentration levels of CO_2 increase. Therefore, the increase in stress could be related to fungi. The effects of carbon monoxide is unclear. Further research is required to confirm this trend which is beyond the scope of this study.

6.5 Conclusion

This study provided an insight into the detrimental effect of $PM_{2.5}$ under a short-term (8 hours) exposure. Furthermore, it was evident that high concentration levels of $PM_{2.5}$ exposure in the indoor environment cause cognitive stress that leads to anxiety, negatively affecting EFs, especially working memory. However, further studies on TVOC and CO_2 electrophysiological responses are required to understand the underlying mechanisms thoroughly.

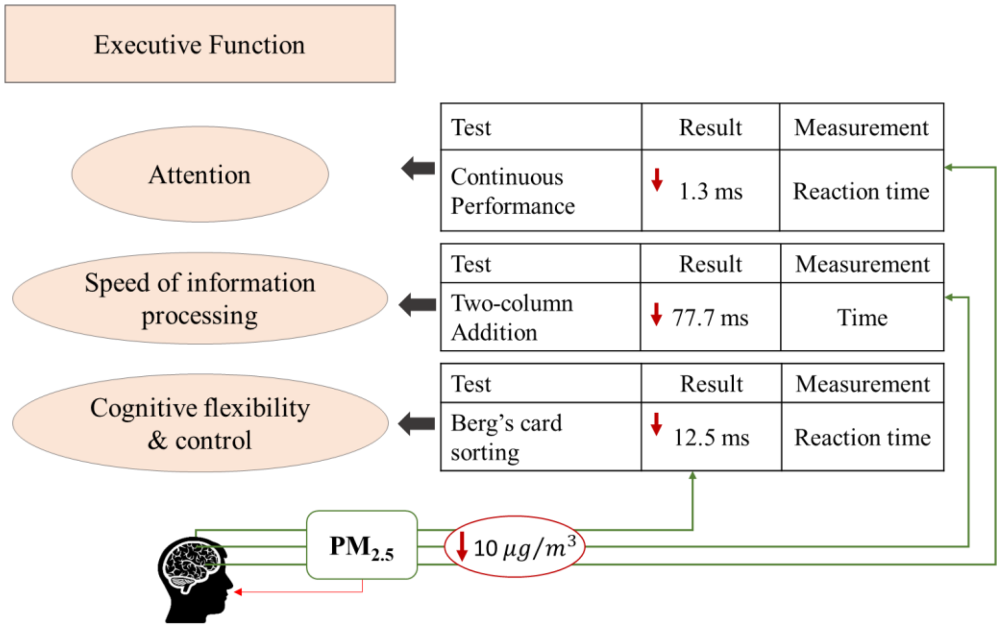
Chapter 7

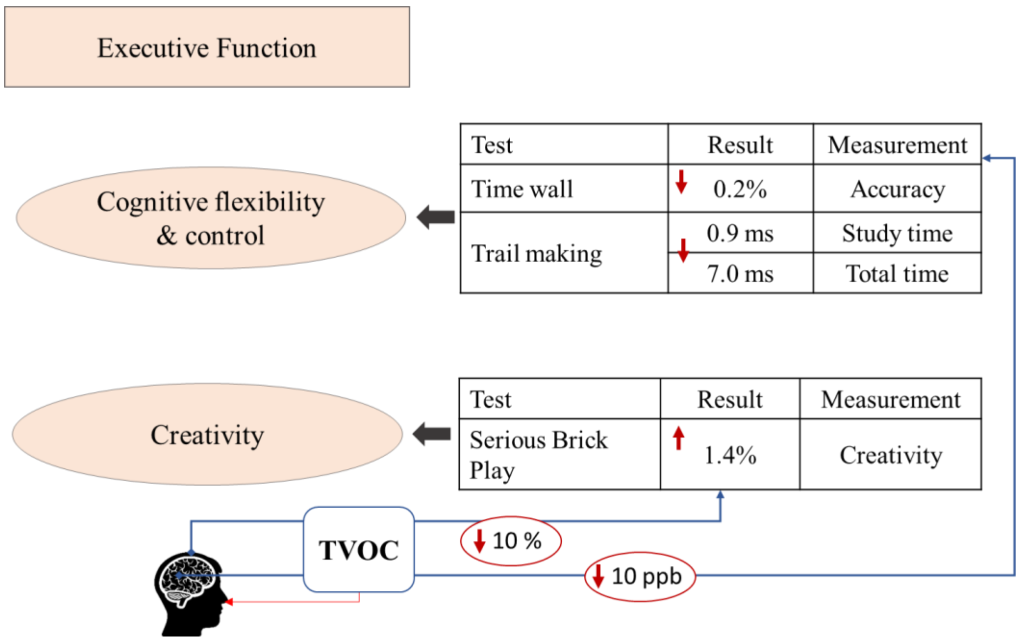
Conclusion and Future Perspective

The chapter concludes with the key findings in answering the identified research gap and research questions stated in Chapter 1. The chapter also highlights the relevance of the key findings and concludes the thesis with limitations of the studies and possible further work.

7.1 Key Findings

The main objective of this PhD thesis was to investigate the relationships between improved IAQ (reduction in $PM_{2.5}$, TVOC, and increase in CO_2 (bio-effluents)) parameters and specific cognitive performance domains (such as creativity, working memory, inhibitory control, cognitive flexibility, speed of information processing, fluid intelligence, and planning). Notably, the increase in bio-effluents indicated the association obtained from the statistical analysis. In a randomised, single-blinded study, the investigation employed different assessment techniques (SBP, cognitive test battery and EEG).





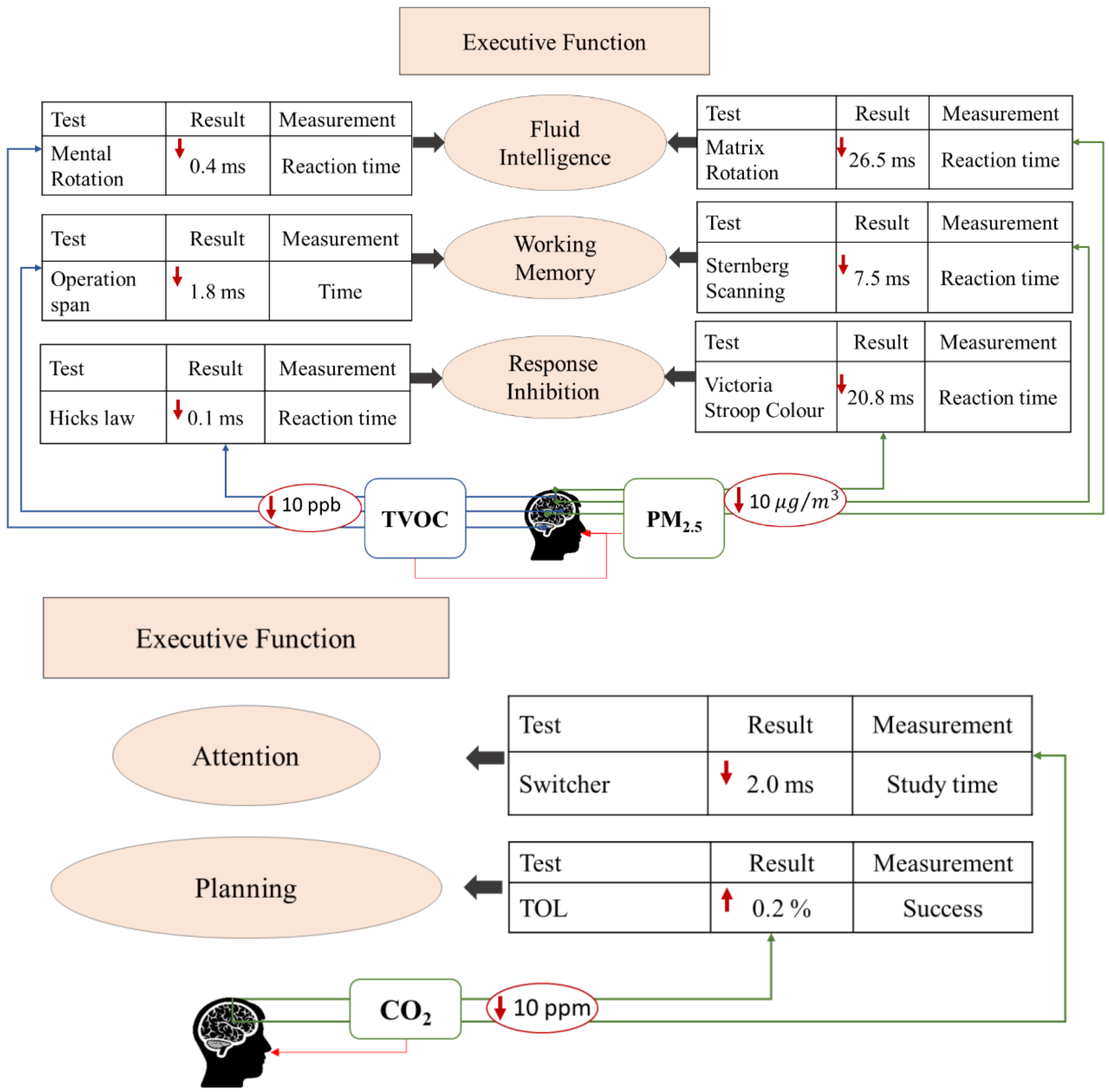


Figure 7-1. Summary of the key findings showing the association of executive functions with IAQ parameters when reduced by 10 concentration levels. The red arrow indicates the increasing or decreasing trend in relation to the mode of measurement parameter (e.g., reaction time, success).

The assessment of cognitive flexibility & control reflects the testing of creativity (Diamond, 2013). The findings from chapter 5, the PEBL test battery on cognitive flexibility & control, complement the finding from chapter 4, assessing creativity through SBP. Both methods revealed the dominant source, TVOC, limiting individuals from reaching their full creativity potential (refer Figure 7-1). The findings from chapter 6, assessing the effects of IAQ parameters through electrophysiological responses, explored possible underlying mechanisms and explanations of the serious impact of the IAQ pollutants such as $PM_{2.5}$ that hold a high tendency to introduce cognitive stress in short-term exposures.

The findings from chapter 5, which studied the impact of IAQ parameters on cognition by employing a PEBL test battery, provide an extensive discussion on specific EFs. Figure 7-1 shows that the small decrement in the concentration levels of IAQ parameters could introduce a more significant effect on one EF than on the other EFs. For instance, a decrement in the concentration of 10 $\mu g / m^3$ of $PM_{2.5}$, speeds up information processing by 77.7ms. The task that assesses attention indicates an increase by 1.9ms with the reduction of $PM_{2.5}$ concentration. The study from Allen et al. (2016) indicates significant effects observed in cognitive domains of 'crisis response', 'information seeking', 'information usage', and 'strategy', which could be classified (according to the structure of EF proposed in this study, see Figure 2.1) as 'planning', 'speed of information processing', 'working memory', and 'cognitive flexibility & control' respectively This classification was deduced as per description provided in Allen's study.

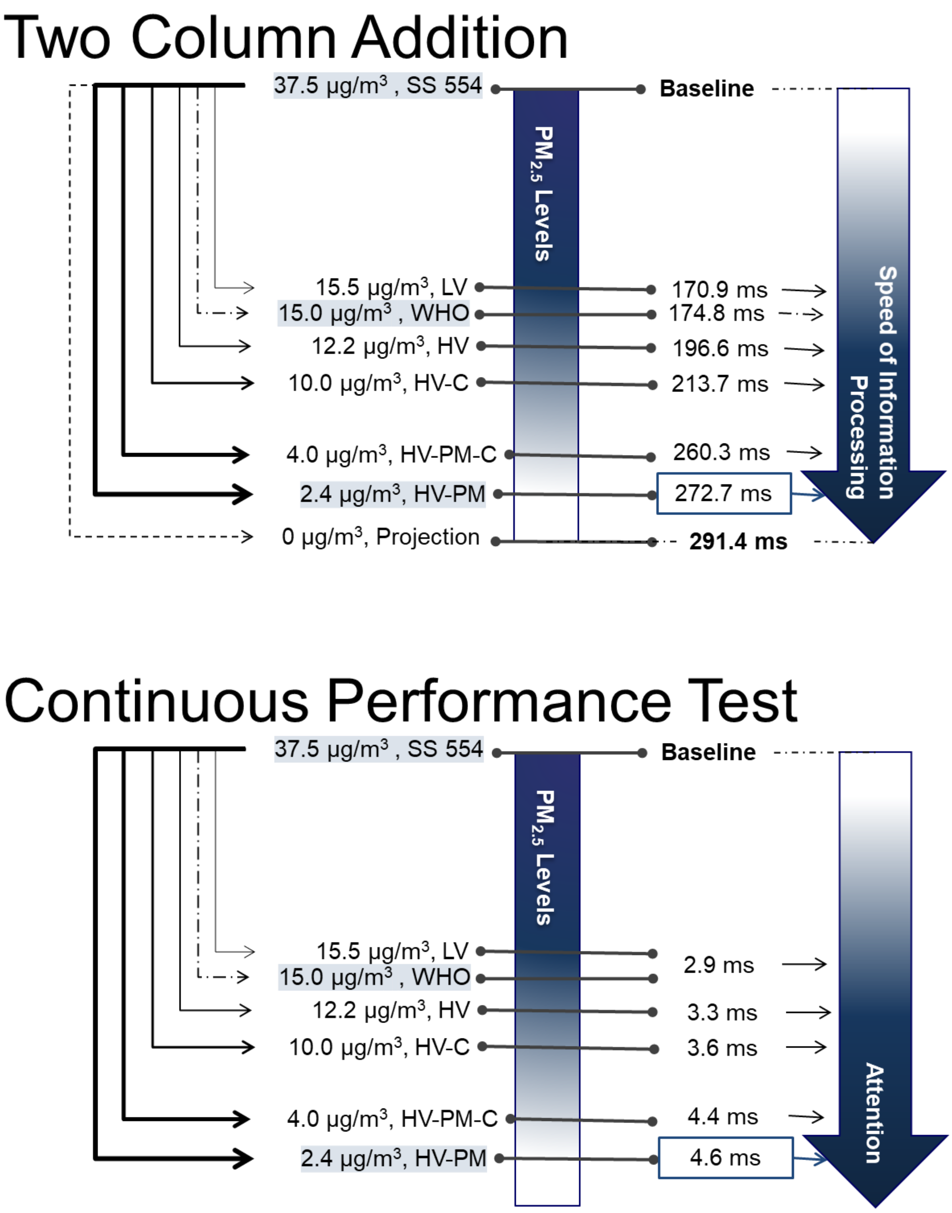
Under elevated CO_2 conditions, a high estimate with statistical significance (1.08) was found in the 'information seeking' domain. In this thesis, the speed of information processing showed effects concerning $PM_{2.5}$. Further examining other experimental parameters reported by Allen showed that $PM_{2.5}$ concentration levels were relatively high compared to the other experimental conditions. This indicates that the effect seen in high CO2 conditions for Allen's findings could be attributed to stress or high arousal (findings from chapter 6). However, the underlying cause could be $PM_{2.5,}$ according to the findings in the thesis. For the high TVOC conditions, a high estimate with statistical significance (2.83) was found in the 'strategy' domain, complementing the current study's finding, where cognitive flexibility & control showed effects in relation to TVOC.

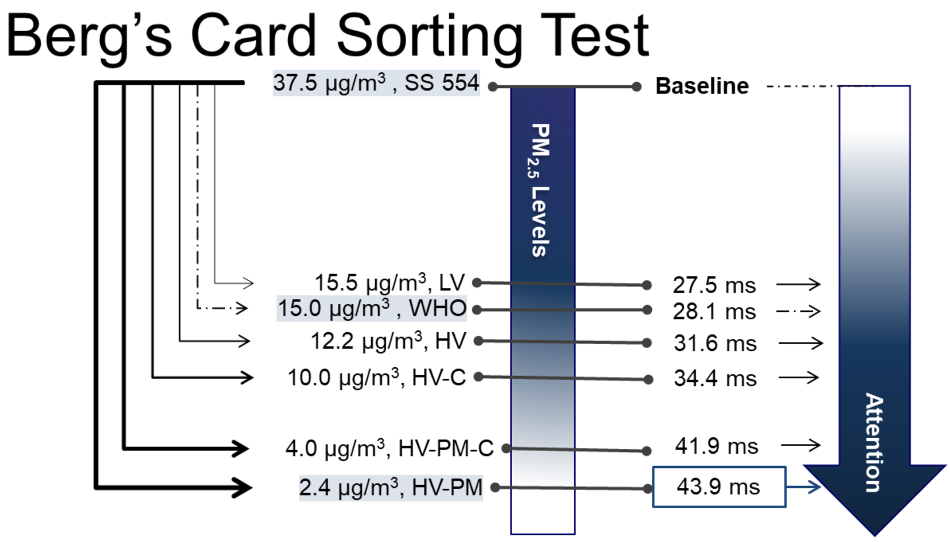
The findings obtained from this study complement and provide further explanation to the effects reported by Allen et al. (2016). However, the cognitive domain specified by Allen covers a border spectrum compared to the more focused EF domains adopted in this study. Thus, introducing uncertainty in comparison of statistical estimates or interpreting the effect. However, inevitably the thesis provides a deeper understanding of how IAQ pollutants affect an individual's cognitive abilities.

7.2 Relevance of the Study

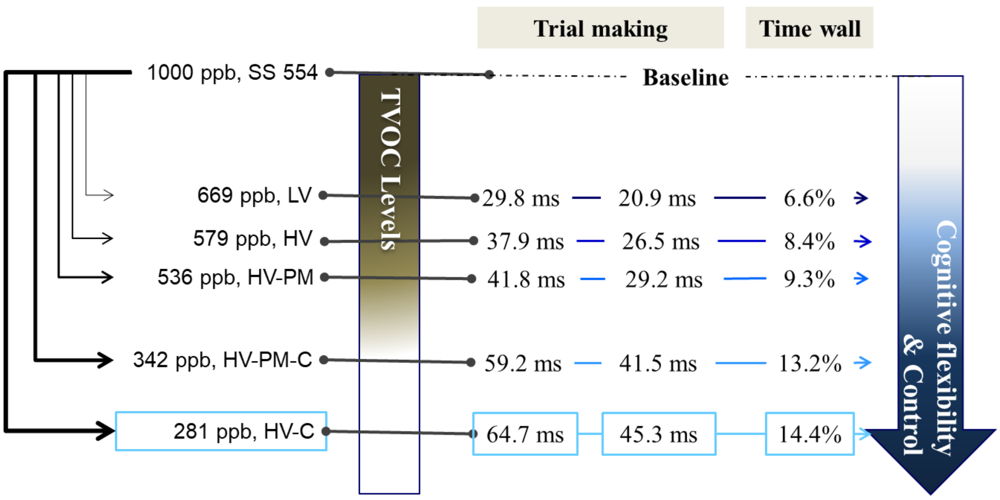
The relevance of the study outcome is iterated in Figure 7-2, showing the effects of the filters on EFs. It is evident that with filters like HEPA the concentration levels are reduced significantly, yielding an increase in performance in different areas of the EFs.

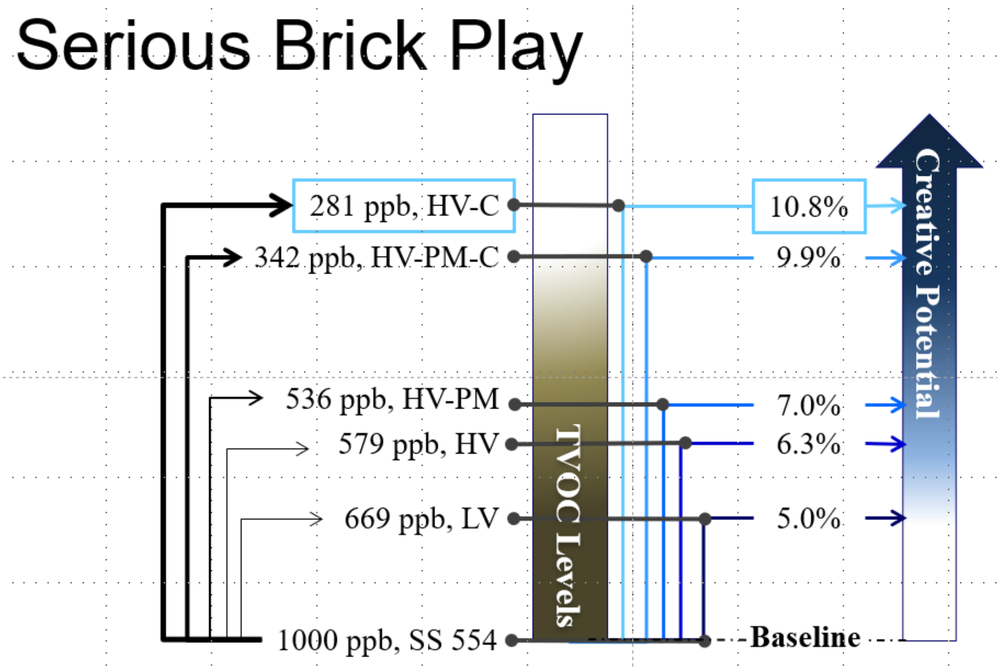
A)



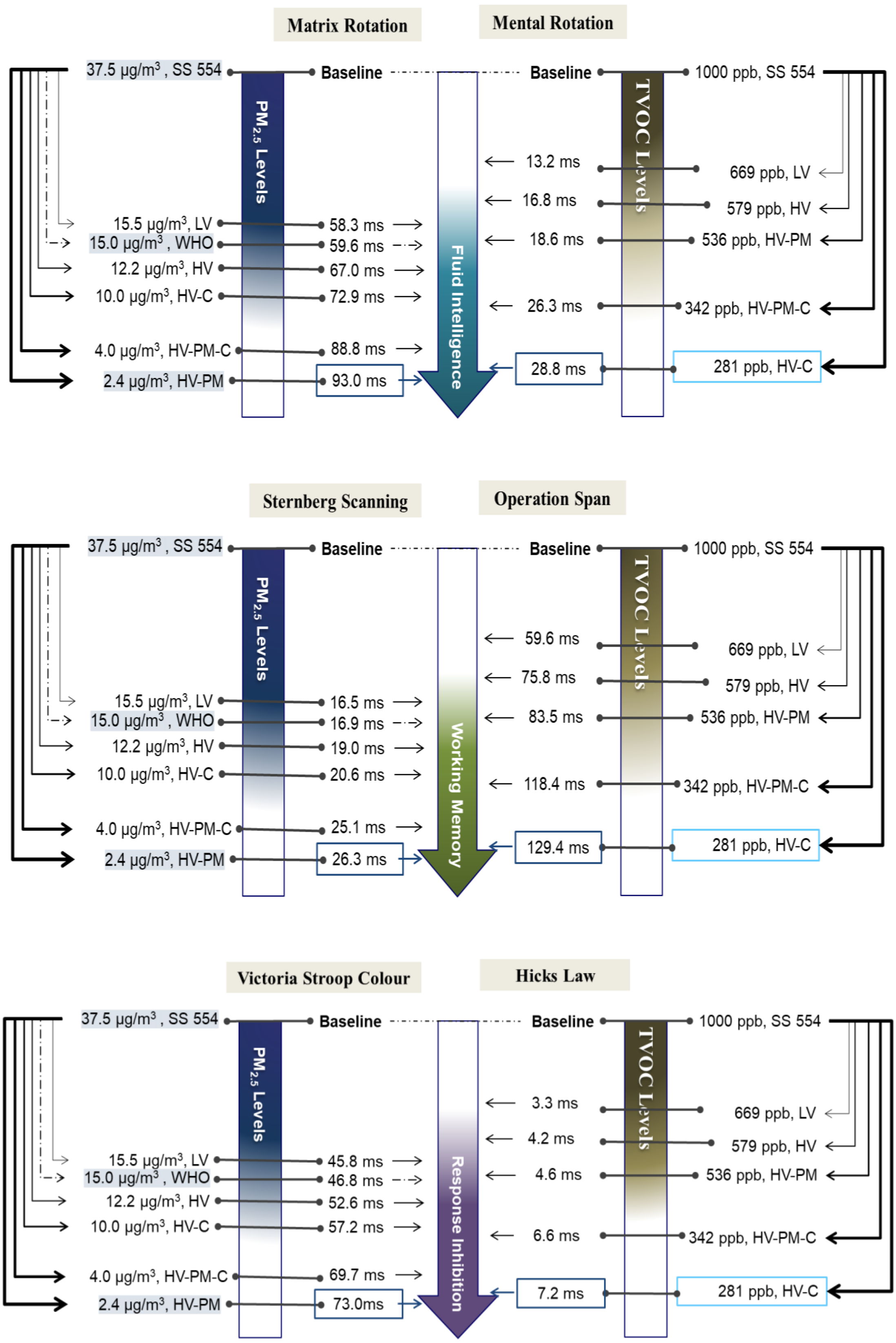

Berg's Card Sorting Test
37.5 µg/m³ , SS 554
Baseline
PM2.5 Levels
15.5 µg/m³, LV
15.0 µg/m³ , WHO
12.2 µg/m³, HV
10.0 µg/m³, HV-C
4.0 µg/m³, HV-PM-C
2.4 µg/m³, HV-PM
27.5 ms
28.1 ms
31.6 ms
34.4 ms
41.9 ms
43.9 ms
Attention

B)


Trial making
Time wall
1000 ppb, SS 554
Baseline
TVOC Levels
669 ppb, LV
579 ppb, HV
536 ppb, HV-PM
342 ppb, HV-PM-C
281 ppb, HV-C
29.8 ms 20.9 ms 6.6%
37.9 ms 26.5 ms 8.4%
41.8 ms 29.2 ms 9.3%
59.2 ms 41.5 ms 13.2%
64.7 ms 45.3 ms 14.4%
Cognitive flexibility & Control


Serious Brick Play
281 ppb, HV-C
342 ppb, HV-PM-C
536 ppb, HV-PM
579 ppb, HV
669 ppb, LV
1000 ppb, SS 554
TVOC Levels
10.8%
9.9%
7.0%
6.3%
5.0%
Baseline
Creative Potential

C)


Matrix Rotation
Mental Rotation
37.5 μg/m³ , SS 554
Baseline
Baseline
1000 ppb, SS 554
PM2.5 Levels
TVOC Levels
13.2 ms
669 ppb, LV
16.8 ms
579 ppb, HV
15.5 μg/m³, LV
58.3 ms
18.6 ms
536 ppb, HV-PM
15.0 μg/m³ , WHO
59.6 ms
12.2 μg/m³, HV
67.0 ms
Fluid Intelligence
10.0 μg/m³, HV-C
72.9 ms
26.3 ms
342 ppb, HV-PM-C
4.0 μg/m³, HV-PM-C
88.8 ms
28.8 ms
281 ppb, HV-C
2.4 μg/m³, HV-PM
93.0 ms
Sternberg Scanning
Operation Span
37.5 μg/m³ , SS 554
Baseline
Baseline
1000 ppb, SS 554
PM2.5 Levels
TVOC Levels
59.6 ms
669 ppb, LV
75.8 ms
579 ppb, HV
15.5 μg/m³, LV
16.5 ms
83.5 ms
536 ppb, HV-PM
15.0 μg/m³ , WHO
16.9 ms
12.2 μg/m³, HV
19.0 ms
Working Memory
10.0 μg/m³, HV-C
20.6 ms
118.4 ms
342 ppb, HV-PM-C
4.0 μg/m³, HV-PM-C
25.1 ms
129.4 ms
281 ppb, HV-C
2.4 μg/m³, HV-PM
26.3 ms
Victoria Stroop Colour
Hicks Law
37.5 μg/m³ , SS 554
Baseline
Baseline
1000 ppb, SS 554
PM2.5 Levels
TVOC Levels
3.3 ms
669 ppb, LV
4.2 ms
579 ppb, HV
15.5 μg/m³, LV
45.8 ms
4.6 ms
536 ppb, HV-PM
15.0 μg/m³ , WHO
46.8 ms
12.2 μg/m³, HV
52.6 ms
Response Inhibition
10.0 μg/m³, HV-C
57.2 ms
6.6 ms
342 ppb, HV-PM-C
4.0 μg/m³, HV-PM-C
69.7 ms
7.2 ms
281 ppb, HV-C
2.4 μg/m³, HV-PM
73.0ms

D)

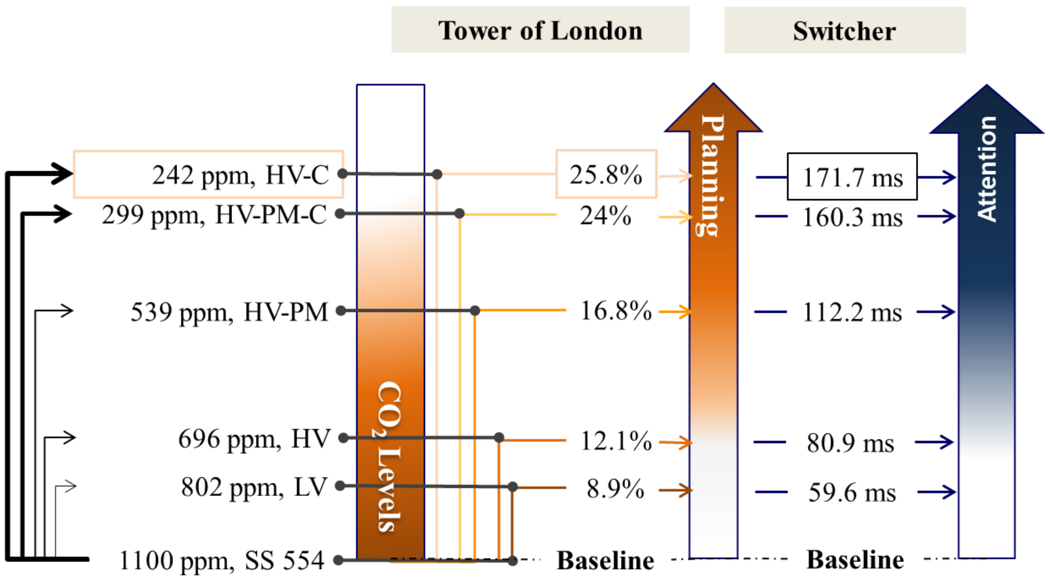


Figure 7-2. Summary of the key findings concerning the experimental conditions, taking SS554 limits as the baseline. A) shows EFs being affected by $PM_{2.5}$, B) shows EFs being affected by TVOC, C) shows EFs being affected by $PM_{2.5}$ and TVOC and D) shows EFs being affected by CO_2. The results are based on the difference between the condition and baseline (e.g., the difference between baseline and LV condition is multiplied by the regression coefficient obtained from the statistical analysis).

Expressing Figure 7-2 in monetary terms for a company of 400 employees, with a minimum wage of S$23 per hour, introducing the same filters increases overall performance by 18.5% over 10 years. The filters are changed annually to ensure efficiency. However, the common practice would be to change the filters when there is a significant increase in pressure. For an individual employee over the space of 1 year, the value of the increased performance is S$1.66. The result is that the short-term effects make it profitable over the space of many years.

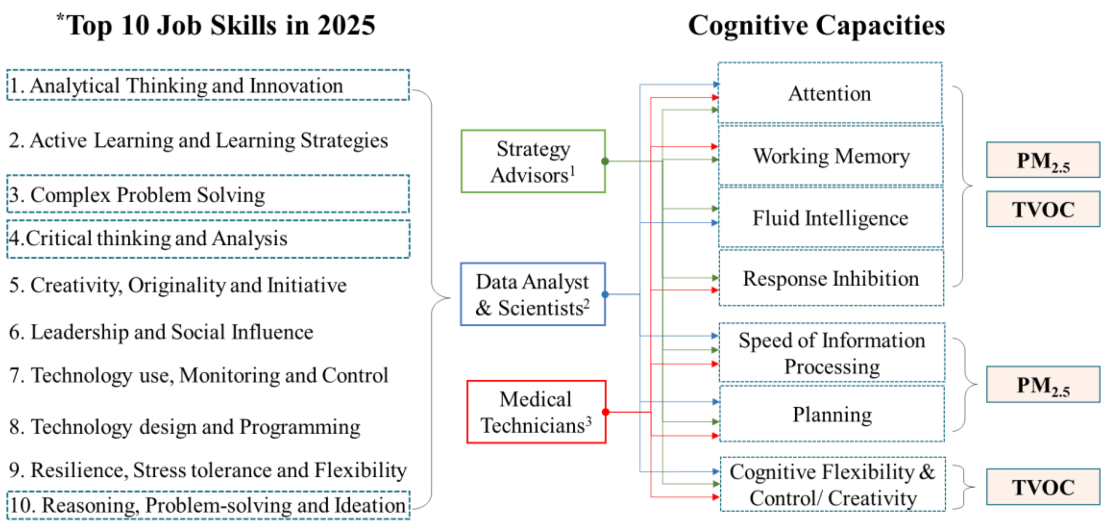


Figure 7-3. Projection of top 10 job skills in 2025 and the relevance of cognitive capacities tested in this study with respect to 3 emerging jobs. [1](Maersk Oil, n.d.), [2](Cognitive Class, 2020), [3](Sedlár, 2020), and *(World Economic Forum, 2020)

The complex network of cognitive abilities makes it difficult to classify a specific cognitive capacity to a specific job title. However, for simplicity, a generalisation of the cognitive abilities network is shown in Figure 7-3. Specific high-skilled jobs, which require high cognitive ability, like data analysts, scientists, or medical technicians, require attention, cognitive flexibility, and control/creativity to fulfil their role within the organisation. A reduction in $PM_{2.5}$ and TVOC levels resulting in improved IAQ makes the employee more efficient. This is required to enable an employee to unleash their full cognitive potential in today's world.

7.3 Limitations and Further Work

Design of Study

The study examined the essential variables of IAQ and considered participants a random variable. Participants could have indicated interaction effects by including variables related to the participants such as BMI, gender, specific demographics such as cultural differences and sleep quality. For instance, some effects of IAQ pollutants could have been more substantial for someone with high BMI than others with low BMI due to the possible oxygen saturation capabilities of the individuals. The current study took account of the confounding variables such as sleep quality and gender differences by introducing power naps and ensuring a 1:1 ratio between the genders; however, it did not examine specific interaction effects of the participants' demographics. Further studies on the variation of BMI, oxygen saturation and cultural differences could indicate how IAQ pollutants affect an individual.

Creativity

Being the first of its kind to study the relationship of IAQ pollutants on creativity, it gives more scope to test the poorly understood but essential cognitive domain, creativity. The SBP is limited to the selection of challenges provided to the participants. The challenge is removing biases present in other creativity tests such as TTCT. Hence, there is limited variation one could adopt for SBP. The derived new methodology requires more testing on a larger pool of participants to determine if the methodology could apply to large sample sizes. As the data for SBP is manually assessed, a different approach is to automate the process for the standardized gradings such as 'usual' or 'unusual' and assessment of the descriptions. Further study is needed to determine the specific mechanism linking pollutants and creativity. In addition, creative cognition is still a new field, using non-invasive techniques such as electroencephalography to study brain waves. At the same time, the participants are engaged in SBP, which could help researchers understand how hands-on, playful tests stimulate creativity.

Cognitive Test Battery

The participants were engaged in various activities before being assessed using the cognitive test battery, PEBL. Despite administrating power nap, participants reflected fatigue. Hence, instead of administrating the test once, at the end of the test day, it could be administered at the beginning of the day and the end of the day. The potential gain is that there could be a comparison of the effect of IAQ on participants varies over the day. The pitfall is that the participants will have strong learning effects that might affect the hypothesis with differences within the study population. A more focused approach could be taken to determine one specific EF (such as planning) rather than a pool of EF. Employing more than one biomarker, such as combining EEG with urine samples, will also deepen the understanding of the IAQ pollutants' biological pathway in a short duration of exposure. Understanding the biological pathways will hence understand which location of the brain are the particles being deposited and the potential neurological hazards/illness that affects cognitive functions (such as Alzheimer's affects attention). This will encourage other building authorities to implement more source mitigation methods in the building premises.

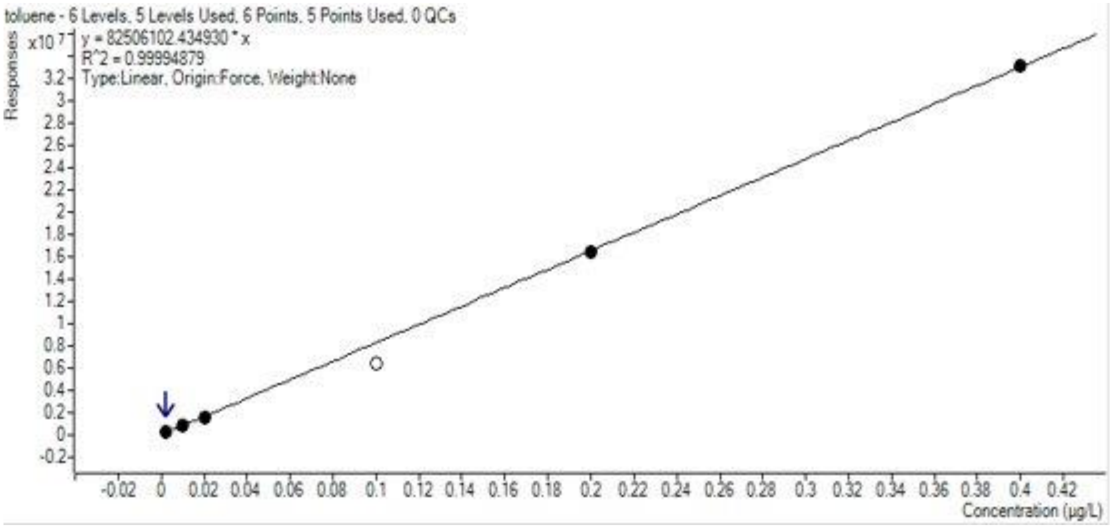
Electrophysiological Responses through EEG

A pioneering study explored the possible impacts of IAQ parameters from electrophysiological responses. However, the data analysis was limited by continuously sampling for 30 minutes while participants were doing a series of tasks from the cognitive test battery, limiting the possibility of correlating the responses to the specific task and the corresponding EF. Further work involves the breakdown of the task (stimuli) and the raw data sampling before moving to the next task. This would make the experimental design more complex because each participant would have to be trained more than once to be comfortable with such procedures.

Over the recent years, some researchers have shown that better IAQ improves the cognitive ability of occupants in the short term. The interdisciplinary approach taken in this thesis showed the impact of IAQ pollutants on cognitive health by employing different facets of assessment (hands-on play, psychological and biomarker), resulting in robust, reliable findings while minimising uncertainty. This creates more room and hopes to inspire future research to understand this essential yet complex problem for a healthier lifestyle. The identified cognitive performance domains are critical for the evolving job market. The scope identified in section 7.3 is not exhaustive but instead functions as preliminary ideas. The field holds uncertainty that needs further investigation. Since it is relatively a new area of focus, little is known about how cognitive functions are correlated to indoor air quality in the long term.

Appendix

Appendix A: GCMS Concentration Calculations



- Usage of linear calibration curve to get RF
- 5 point calibration of Toluene (1 ppm to 200 ppm)
- Volume spiked in for calibration – 0.2 mL
- Volume sampled – 68*60*8=0.03264m3
- Results obtained from CEE/NEWRI

Area under the graph * Response factor -> x [ug/mL]

ppbV = $x\left(\frac{0.2}{0.03264}\right)\left[\frac{\mu g}{m3}\right] * \left(\frac{1}{28.9647}\right) * 8.3144 * 297.15 * \left(\frac{1}{101.325}\right)$

$$RF = \frac{Peak\ Area}{Sample\ Amount}$$

Molecular Weight dry air – 28.9647 [g/mole]

Universal gas constant (R) - 8.3144 [L.kPa/mol.K]

Room Temperature - 297.15 [k] -> 24 C

Air pressure - 101.325 [1 atm]

Appendix B: Pilot Study

The pilot study comprises two parts broken into morning sessions and afternoon sessions in an 8-hour protocol. The handpicked activities administered in the morning session were tested for feasibility through the participants' feedback to be included in the finalised morning protocol. The afternoon session was to redefine the designed protocol, test the difficulty of the psychological test battery, and the protocol of administrating EEG.

7.3.1 Alternative Uses Test (AUT)

The AUT required participants to list as many different uses as possible of an everyday object. For instance, a brick, the primary use is building. An alternative use could be using it as a phone. Participants were instructed to list down as many alternatives uses as possible in 10 minutes. The objective of this activity was to determine creativity. Two objects were tested for 10 minutes (i.e., Day 1 - Knife and Brick, Day 2 – Door stopper and Frisbee, and Day 3 – Clock and Sock). The data from the activity was collected in a soft-copy document. Then, 3 graders graded the consolidated responses upon originality (each response is compared to the total responses,), fluency (total number of responses received from an individual), flexibility (number of categories determined by graders), and elaboration (amount of detail,). A high score translates to being more creative. AUT results were dependent on the participant’s familiarity with the listed objects, and over a longer length of study, maintaining the familiarity of all listed objects would be challenging.

Table A-1. Points allocation to grade AUT (Bonk, 2019)

Factors	Sample of rules	Points
Originality	Unique responses up to 5% of the total	1
	Unique responses up to 1% of the total	2
Elaboration	"a knife"	0
	“a knife to slice lemon with to make iced lemon tea”	2

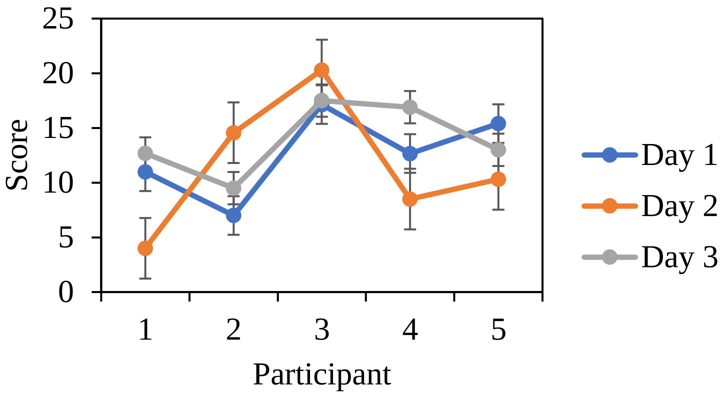


Figure A-1. Line plot representing total AUT scores of each participant with error bars indicating standard error of the mean (SEM). The responses were scored according to the grading method described by Bonk (2019).

The lines in plot Figure A-1 represents the total score of each participant over 3 days. The results do not show a clear trend. Between the 3 days, participant 1 and 2 scored the lowest for day 1 and the participant 1 and 4 scored the lowest for day 2. This shows that participants' ability to think out of the box was based on the given object's familiarity, but this conclusion is subjective due to the small sample size. Despite what was reflected from the data, participants found the activity was engaging and rated the activity as a medium challenge. The duration was sufficient.

7.3.2 Typing Test

The typing test is a commonly used task to measure the productivity of the occupants. Previous studies used typing tests to measure productivity (Doroff et al., 2019; Kosonen & Tan, 2004b; Ojo et al., 2018). These studies had participants to type out a printed text as much as possible within the stated duration.

Participants had to copy an Estonian essay from a PDF file (to prevent 'copy-paste') to a word document as much as possible in 10 minutes. All special characters were removed from the PDF copy. Each Estonian essay is a combination of different random blog articles approximating 600 words. Participants were instructed that they were not allowed to use the backspace button to make it more challenging. Participants were given different essays to type every day. The objective of the task was to determine the participants' productivity through the measurement of words per minute (WPM) count and accuracy. The words per minute count and accuracy were calculated according to the following Equations (3-5 to 3-6):

$$\text{WPM} = \frac{\text{Total words typed}}{\text{Duration of task (minutes)}} \quad \text{(A-1)}$$

$$\text{Accuracy, \%} = \frac{(\text{Total words typed} - \text{Number of errors})}{\text{Total words typed}} \times 100 \quad \text{(A-2)}$$

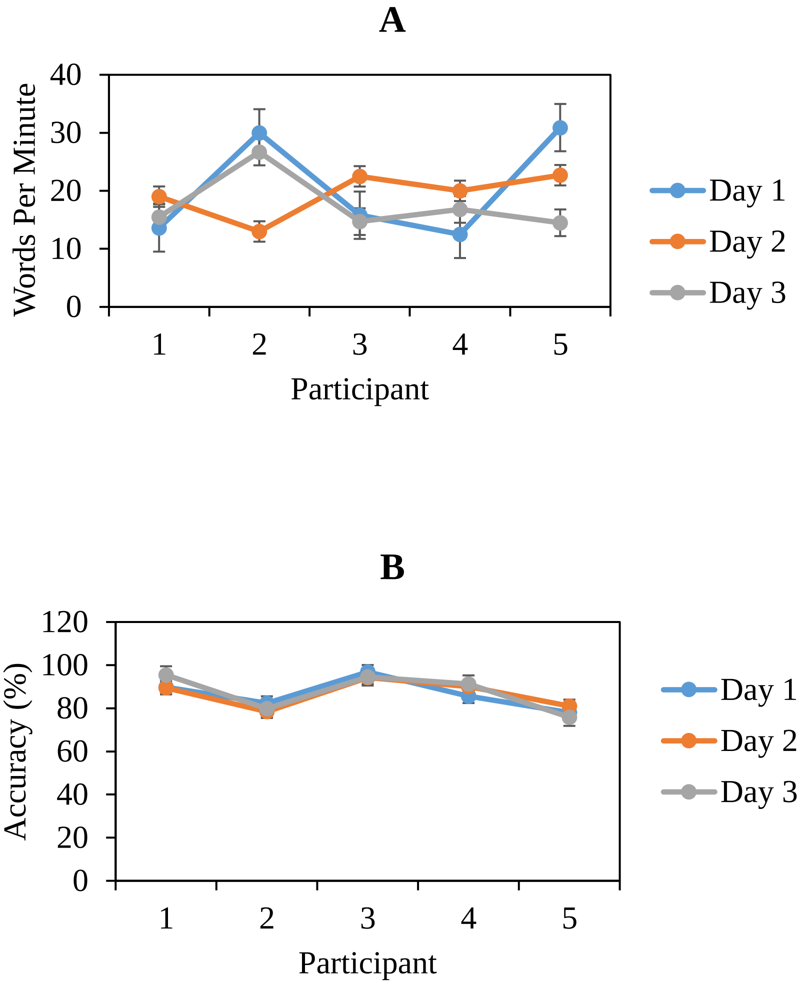


Figure A-2. Line plot for typing test with error bars as the standard error the mean (SEM). A) Indicates how much did 5 participants type in 10 minutes. B) Indicates how accurate the 5 participants typed those words.

The results from Figure A-3 showed inconsistent fluctuations of WPM with relatively high accuracy of 90%. A possible modification was to allow participants to use the backspace to reduce the WPM rate and increase accuracy. Participants rated the activity easy but engaging, and 10 minutes deemed sufficient.

7.3.3 Mirror Tracing

The mirror tracing task was used to test visual perception and motor coordination skills. Over the years, the device used to administer and measure the task had evolved from using a Lafayette model 31010 mirror tracing device to a tablet computer (Borresen & Klingsporn, 1992; Fourneret & Jeannerod, 1998). For simplicity, we adopted the traditional means to administer and measure the activity, where the tracing was done on pieces of paper.

Participants were given six (4 rows of 3) different geometric patterns that increased its geometric complexity (see Figure A-3(A)). Then, they were required to trace on the boundary lines of the pattern from the starting point indicated by a black dot as quickly and accurately as possible, using both hands in the opposite direction (left hand – anticlockwise and right hand – clockwise) under the supervision of the moderator. The objective of the task was to determine the participants' accuracy through the mean error and time taken to complete the task.

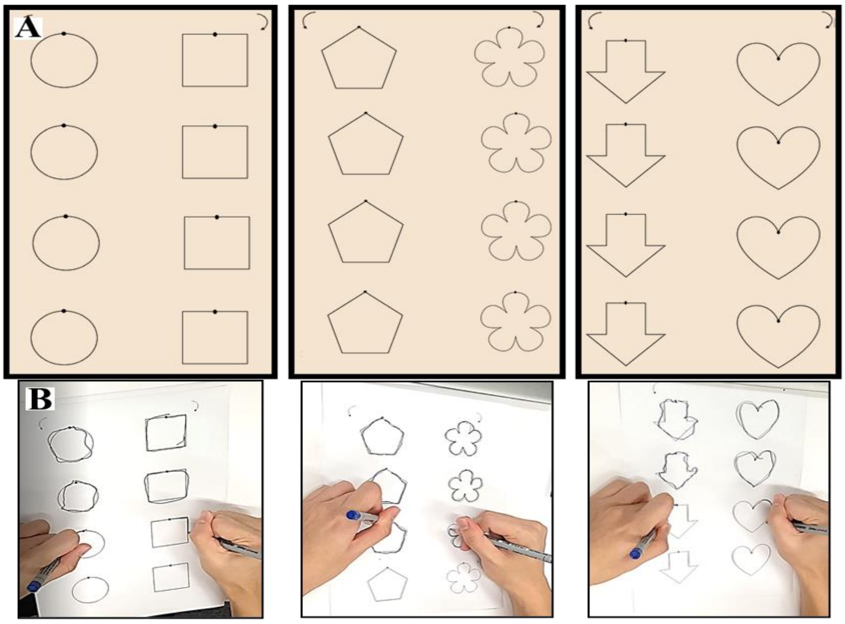


Figure A-4. Example of geometric pattern given to participants.

The error scores were computed following the guidelines where an error is considered if the trace is outside of the boundary lines or there was an excessive tracing of more than 1 cm. Each time such error occurs, it was considered as a separate error. However, efforts to remove the learning effect must be taken into consideration.

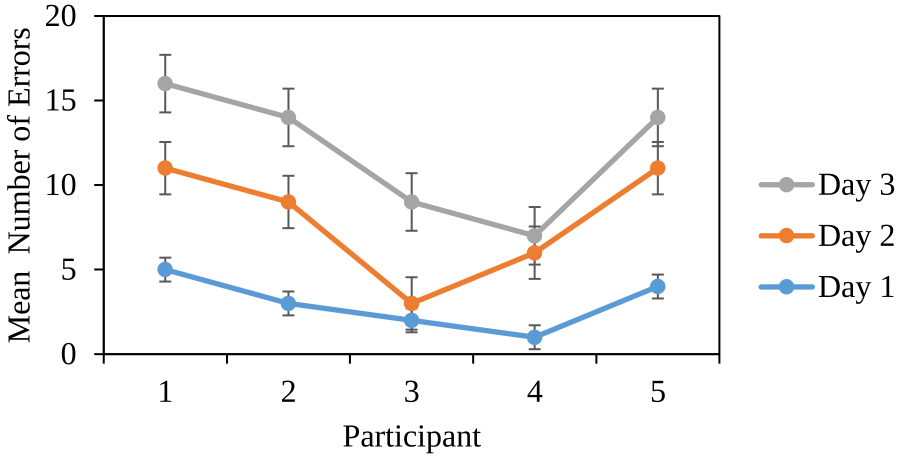


Figure A-5. Line plot for mirror tracing with error bars as the standard error of the mean (SEM).

The SEM from the figure above, Day 1 showed a better accuracy trend over the computed mean than Day 2 and 3 averages. This could be due to the learning effect (Newell & Rosenbloom, 1981) and negligence of tracing accurately as the complexity increases. Participants felt the increasing complexity of the shapes and the coordination of different directions to trace was the competitive edge with more than enough time to complete. Mirror tracing has the same disadvantage as the geometric figures maintaining the same difficulty for a longer length of study.

7.3.4 Incomplete Drawings

The incomplete drawing task was inspired by the Torrance Test of Creative Thinking (TTCT) (Jankowska & Karwowski, 2015) where it assesses creativity through imagination. Participants were given five pages of incomplete lines, as shown in **Error! Reference source not found.** A-5(A),and were instructed to complete it as they prefer Figure A-5(B). The incomplete drawing was tested on Day 1 for 25 minutes. The objective of the task was to determine the creativity score of the participants in creating and visualising objects.

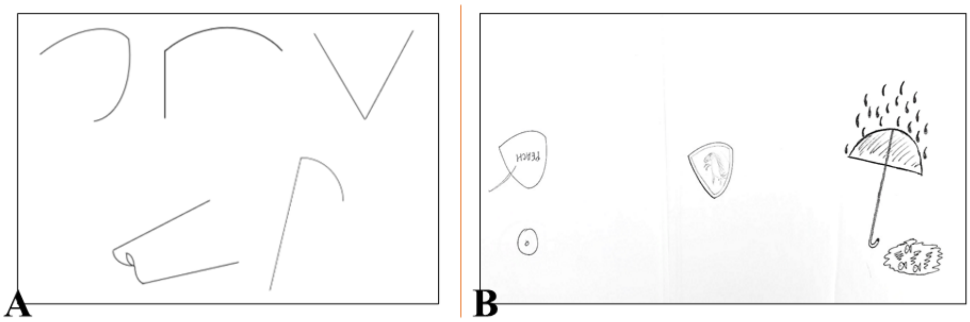


Figure A-6. Incomplete drawing task with 5 incomplete lines presented to participants to complete. **A** – represents the five incomplete lines given to participants, and **B** – represents a participant completing three of these lines.

This test was proven to be accurate and reliable only if professionally trained judges scored the entries (K. H. Kim, 2006). Therefore, it was proposed to have 3 professionally trained psychologists in the scoring system to score the entries. Some participants felt that the drawings get repetitive, and the others felt it was draggy and boring. The research team observed that the participants were not engaged in the activity. Therefore, the incomplete drawings task was removed from the protocol as it was deemed unsatisfactory.

7.3.5 Origami

The ancient Japanese art of folding papers into 3-dimensional objects in a particular manner and order is known as Origami. Studies had shown that origami could be used to test spatial abilities (R. J. Lang et al., 2016; Lewis & Frank, 2013; Tenbrink & Taylor, 2015). Participants were provided with a piece of origami paper and a 14-minute YouTube video (Paper Kawaii - Origami Tutorials, 2016). It was instructed to use the video to complete the task (see Figure A-6). The task was tested on Day 1 for 45 minutes. The objective of the task was to determine the folding success rate.

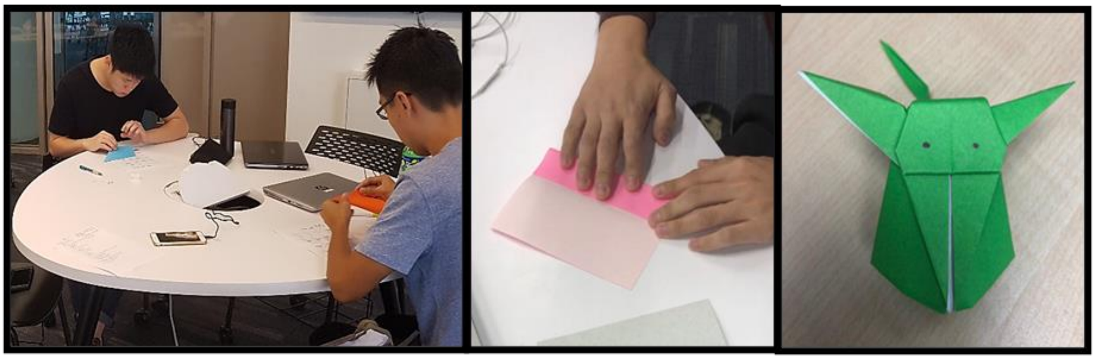


Figure A-7. Participants were involved in creating origami Pikachu with the aid of a step-by-step YouTube video. The green Pikachu was the product of the participant.

The final product was compared to the original picture shown in the YouTube video (Tenbrink & Taylor, 2015). For simplicity, we gave a score of 1 to completed origami, rating it as success, and 0 to an incomplete origami rating it as unsuccessful. The time taken for the participants to complete was noted. This made the activity inconsistent among different participants. Only two participants who had prior experience with origami managed to complete the task and was fast in completion. This created too much idling time for waiting for other participants to complete the task. In addition, participants felt that the task was draining and required specialised knowledge on technical jargon to complete it. The research team saw the task as having the potential of drawing a biased conclusion on spatial abilities. Therefore, origami was removed from the protocol as it was deemed unsatisfactory.

7.3.6 Tetris

Tetris is a computer game that involves rotation and fitting together visually presented blocks of different shapes and colours. The game has been reported to benefit visuospatial working memory. Tetris used for the study was a free online game (Tetris Holding, 2021). Participants were required to use the keyboard arrow keys to move, rotate at 90 degrees, or accelerate down as the randomly shaped geometric blocks falls to the bottom of the playing screen (see Figure A-7). The game was tested on Day 2 for 30 minutes with 5 minutes of practice. The game's objective was to create horizontal lines that disappear from the screen where points were awarded. If the blocks stack up to the top of the playing screen, the game ends with an automatic final score output. Participants were told to restart the game and were instructed to reach a higher score for each play.

Figure A-8. Screenshot of Tetris online game designed with 25 levels (Tetris Holding, 2021). The game screen on the right shows the different geometric shapes falling from the top of the playing screen.

Cumulative scores of each game were manually recorded for the duration. Participants felt that the duration given was long and draining. However, the game was engaging at the beginning with repeated plays, and it became boring. A study from Lau-Zhu et al. (2017) highlights the need for more studies to conclude the benefit of visuospatial working memory. Therefore, with a reduction in duration, Tetris was included in the protocol as a *filler* game.

7.3.7 Lego

Lego (The LEGO Group, 2021), a famous children's play, comprises interlocking plastic bricks with a range of complimenting gears and figurines used to construct objects. Previous studies had used these bricks as a tool to support creativity or creative thinking among participants (Gauntlett, 2014; Moreau & Engeset, 2016; Peabody & Noyes, 2017; Stockmann & Graf, 2020). Lego was used for two tasks where one was called Focused Lego, and the other as Unstructured Lego.

The focus Lego requires the participants to recreate four structures with reference to the monochrome step-by-step guide from LEGO (see Figure A-8). The monochrome guide was an effort to increase the difficulty of the building process by preventing participants from sorting the bricks according to the colours before building. The task lasted for 45 minutes. The objective of the task was to allow participants to get familiar with the possibilities of building complex structures while problem-solving (putting together the bricks).

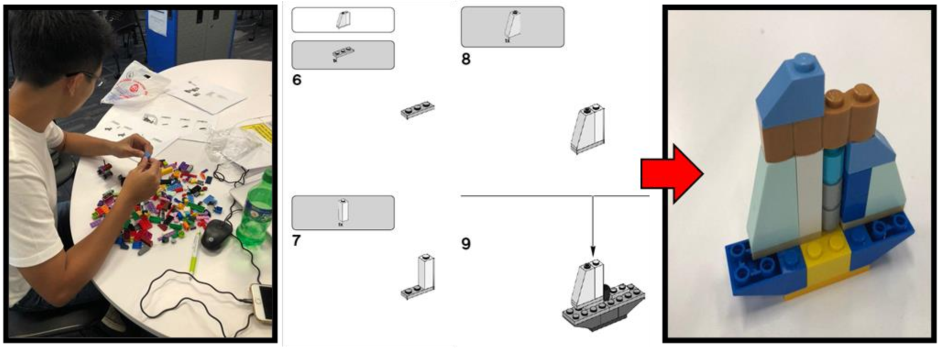


Figure A-9. Focused Lego with monochrome step-by-step guidelines resulting in a ship structure (middle to the right). Shows participant being engaged in the activity.

The completed structure was then examined for mistakes. For each mistake, a point was awarded. In most of the cases, participants did not make any mistakes. Participants felt the task was refreshing, but it was too long. Participants were able to complete the task in 20 minutes and were idling till the time ran out. The research team culminates that it was futile to grade the task instead of having it as a filler activity for participants to get familiar with building with Lego, reducing duration.

The unstructured Lego, an inspiration from Moreau & Engeset (2016), required participants to create anything they wanted from a given pile of bricks in 30 minutes (Figure A-9, shows a built example). At the end of the build, participants had to write a short description. The objective of the task was to determine the participant's creativity through forming and describing their structure.

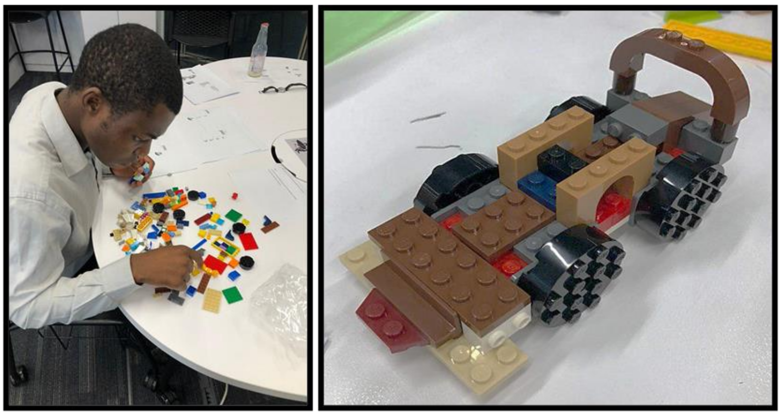


Figure A-10. A built sample from Unstructured Lego.

A possible way to determine creativity was to have the built grade by 3 trained psychologists based on the idea, fluency of the description and the ability to present different ideas. Participants found the task to be fun and challenging. Despite engaging actively, they felt the instruction was vague. Hence, it was suggested to instruct on creating objects surrounding a theme. The activity then took the form of Serious Brick Play.

7.3.8 Psychological Tests and EEG

The psychological test battery was administered through PBEL, an open-source software (Mueller & Piper, 2014). The aim was to obtain feedback on the level of difficulty for each of the selected tests. The feedback helped to select, modify, and remove the test if required in the test battery.

Two participants volunteered for testing with EEG headsets (Figure A-10) while answering the PEBL test battery. The aim was to observe the user-friendliness and the comfort of the headset for a long duration. However, prolonged usage of the headset caused the electrodes to dry up, which increased discomfort for participants. The discomfort experienced might hinder participants' performance in the test battery. Hence the test battery was rearranged in a way where a similar cognitive function test was tested twice. The first half test was done with the EEG testing. Once completed, participants were to stop recording and complete the rest of the tests in the battery. This allowed participants to use the headset without any discomfort.

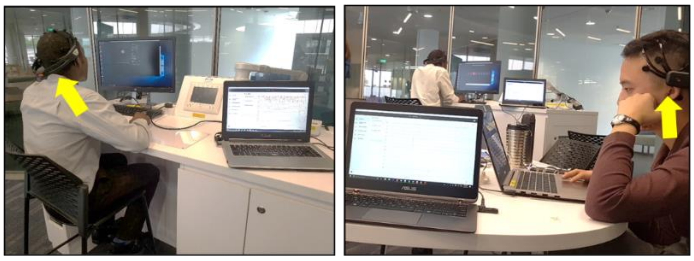
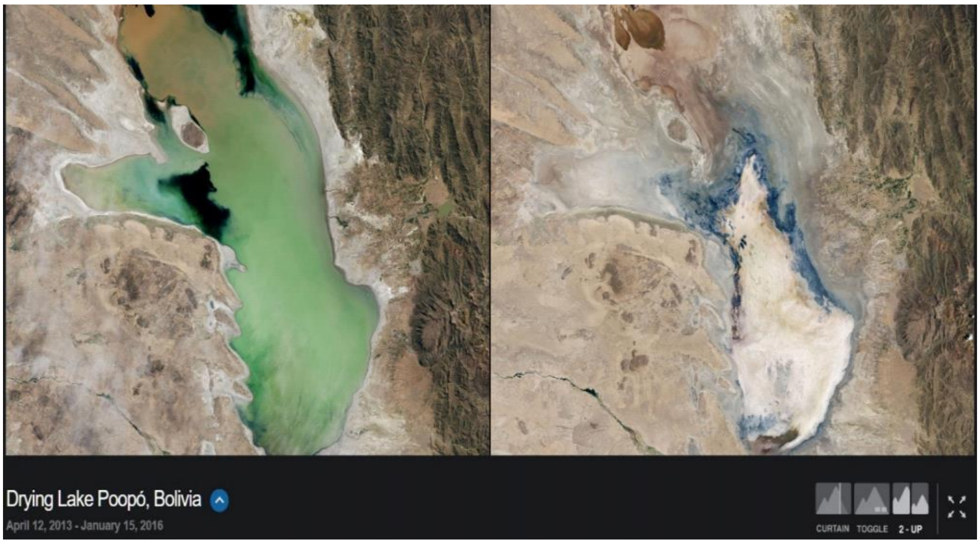


Figure A-11. Participants with the EEG headsets on and completing the PEBL test battery tasks.

Appendix C: Challenges

Climate Change



Source: NASA's images of change (https://climate.nasa.gov/images-of-change?)

The images above representing different landscapes over a different part of the world were taken over different time frames (e.g. over the years or months). The enormous change seen in these images reveals the devastating outcomes of climate change due to human activity. The unmitigated greenhouse gas due to human activities has been anticipated to increase the global temperature from 2.6ºC to 4.8ºC by 2100. Greenhouses gases, such as carbon dioxide, trap heat in the atmosphere and regulate our climate. These gases exist naturally, but humans add more carbon dioxide by burning fossil fuels for energy (coal, oil, and natural gas) and by clearing forests. Greenhouse gases act like a blanket. The thicker the blanket, the warmer our planet becomes. At the same time, the Earth’s oceans are also absorbing some of this extra carbon dioxide, making them more acidic and less hospitable for sea life.

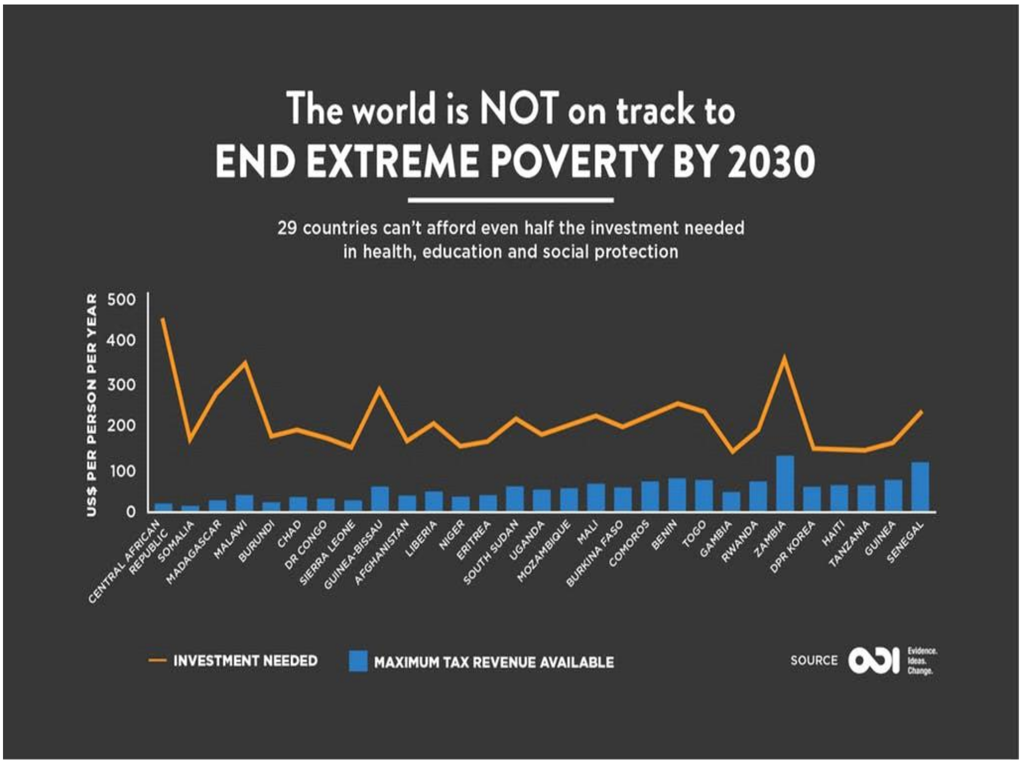
Humans and wild animals face new challenges for survival because of climate change. More frequent and intense drought, storms, heat waves, rising sea levels, melting glaciers and warming oceans can directly harm animals, destroy the places they live, and wreak havoc on people’s livelihoods and communities. As climate change worsens, dangerous weather events are becoming more frequent or severe. People in cities and towns are facing the consequences, from heat waves and wildfires to coastal storms and flooding.

As such, what could be done to slow down climate change?

You are required to build a model with the Lego bricks by expressing your solution on to this building challenge.

Upon building give a description of your model below.

Poverty



Poverty entails more than the lack of income and productive resources to ensure sustainable livings. Its manifestations include hunger and malnutrition, limited access to education and other basic services, social discrimination and exclusion, as well as the lack of participation in decision-making. According to the UN, the current statistics refers to more than 780 million people live below the international poverty line. 11% of the world population lives in extreme poverty. By 2030, 167 million children will live in extreme poverty if nothing is done.

Singapore, known as one of the wealthiest countries in the World with a GNI per capita of US$90, 570 as of November 2018 is also one of the countries in the world with large income gap. Recent statistics reveal that 1 in 10 Singaporeans are unable to meet basic needs in the form of food, clothing, shelter and other essentials. The top 20% of earners saw their real wages rise by 27% where the bottom 20% of earners saw their real wages fall by 8% between 1998 and 2010.

While the government tries to implement policies forcing on poverty, it is also essential to understand the complexities of poverty. Children from low-income families are more likely to experience developmental delays and learning difficulties compared to their peers. They are also more likely to experience anxiety, depression and problems with impulse control. Research had shown that the impact of the toxic stress of poverty on children's brain development, which sometimes continues into adulthood. Employment assistance programmes may help with money and give them the confidence to secure a job, but will not eradicate this scourge of poverty.

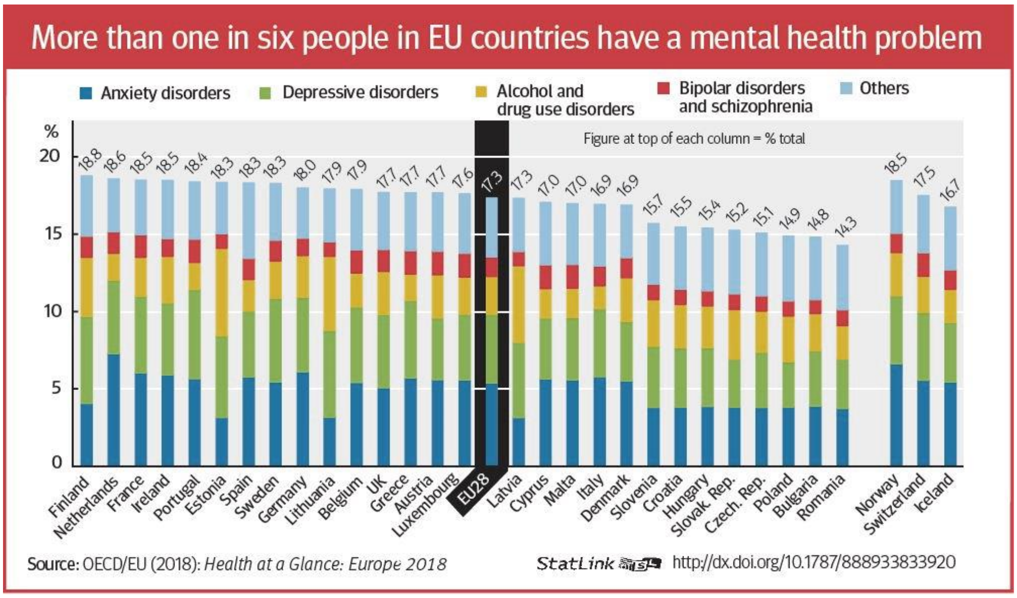
As such, what could be done to change/improve the state of poverty?

You are required to build a model with the Lego bricks provided by expressing your solution about this building challenge.

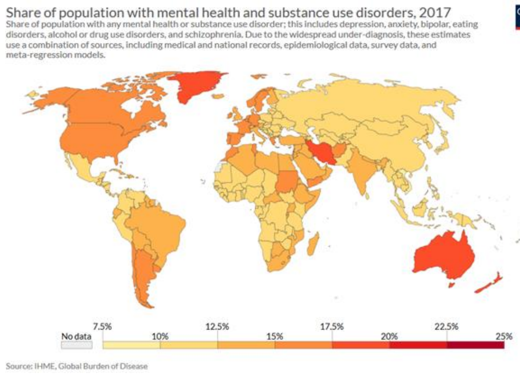
Upon building give a description of your model below.

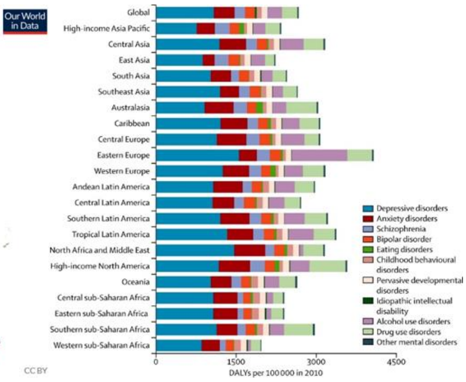
Mental Health

Finland is rated one of the happiest countries on earth, according to the World Happiness Index Report, 2018. However, mental health statistics depict a different scenario as shown below.



Mental health and behavioural problems (e.g. depression, anxiety and drug use) are reported to be the primary drivers of disability worldwide, causing over 40 million years of disability in 20 to 29-year-olds. Major depression is thought to be the second leading cause of disability worldwide and a significant contributor to the burden of suicide and ischemic heart disease. Mental health is the new global crisis that is a growing public health concern where in 2018 the WHO (World Health Organisation) Director-General identified mental health for accelerated implementation within WHO's work. It is estimated that 970 million people worldwide had a mental or substance use disorder in 2017.





From the chart on the left shows that globally, mental and substance use disorders (comprises a range of disorders including depression, anxiety, bipolar, eating disorders, schizophrenia, intellectual developmental disability, and alcohol and drug use disorders) are very common: around 1-in-6 people (15-20%) have one or more mental or substance use disorders.

The breakdown of the disorders shown on the chart (right), had used data from the Global Burden of Diseases, Injuries, and Risk Factors Study 2010 to estimate the burden of disease attributable to mental and substance use disorders in terms of disability-adjusted life years (DALYs). Among all continents, South East Asia, depressive disorders are one of the highest.

In Singapore, a recent study done in 2016 found that 1 in 7 people in Singapore (13.9 per cent) have experienced specific mood, anxiety, or alcohol use disorders in their lifetime whereas in EU it is estimated that 1 in every 6 people experience a mental health problem. This proportion is an increase from roughly one in eight (12 per cent) six years prior.

Mental health is a major concern when it comes to well-being as such what could be done to change/improve this state?

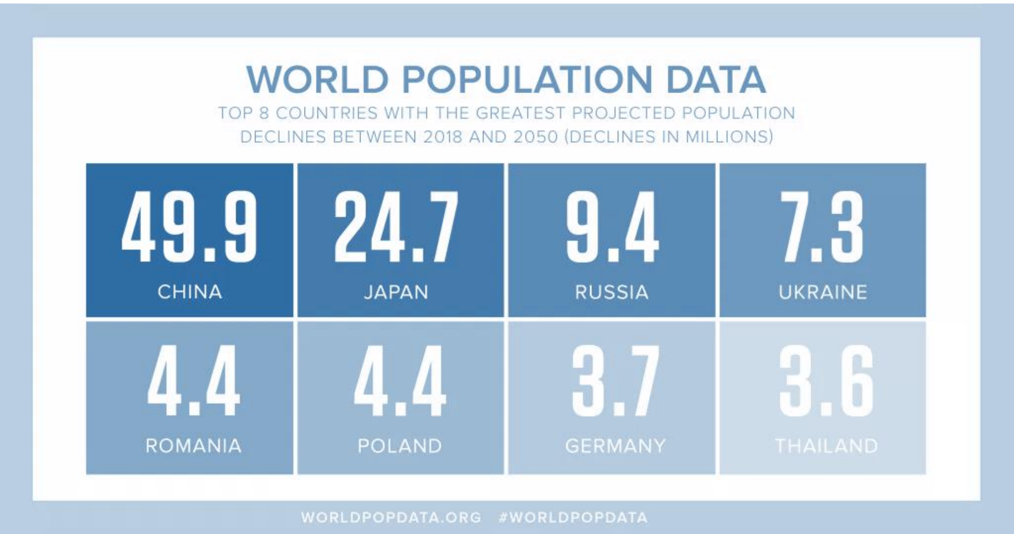
You are required to build a model with the Lego bricks provided by expressing your solution about this building challenge.

Upon building give a description of your model below.

Ageing Population

Virtually every country in the World is experiencing growth in the number and proportion of older persons in their population. Globally, the number of persons aged 80 or over is projected to triple by 2050, from 137 million in 2017 to 425 million in 2050. By 2100 it is expected to increase to 909 million, nearly seven times its value in 2017. As many such countries are likely to face fiscal and political pressures about public systems of health care, pensions and social protections for a growing older population.

From the statistics above, these top 8 countries are projected to have an increasing population. **Nigeria will become the third most populous country as its population rises to 411 million,** up 109% from 2018. Nigeria is currently the seventh most populous country.

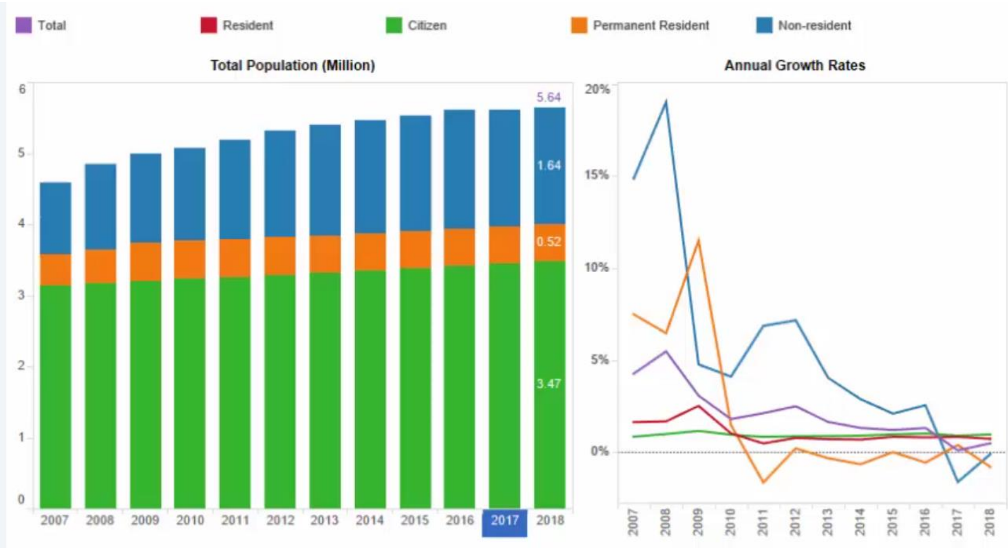


Top 8 countries listed in the table above are projected for the decline in population by 2050. **A total of 38 countries will have smaller populations in 2050 than in 2018.** China will register the most substantial numerical population decrease, about 50 million followed by Japan at 25 million and Russia at 9.4 million. Romania will see the most significant percentage decline in population (23 %). **China's population will decrease by about 50 million from its current size to**

1.34 billion. India will supplant China as the world's most populous country with 1.68 billion people.

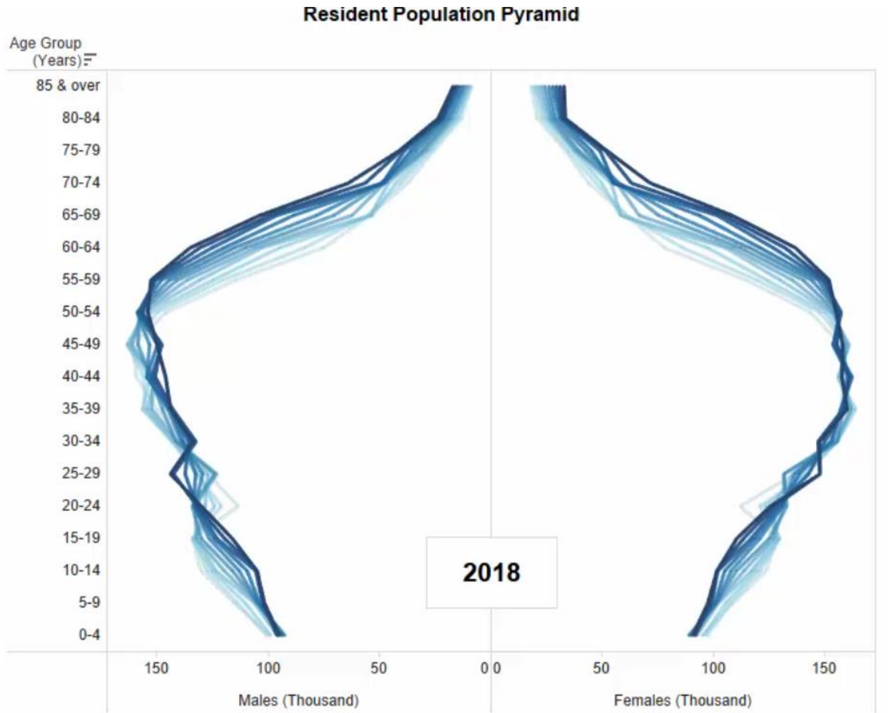
The size and age composition of a population is determined jointly by three demographic processes: fertility, mortality and migration. Declining fertility and increasing longevity are the key drivers of population ageing globally; international migration has also contributed to changing population age structures in some countries and regions.

For the past 11 years in Singapore, the growth rates among the population have been more stagnant than ever. As shown in the figure below, total population growth in 2018 was 0.5% (compared to 0.1% in the previous year). Resident growth has remained stable since 2012.



Singapore population demographics over 11 years

As projected that life expectancy of Singapore population will rise further due technology advances. The life expectancies for men and women born in Singapore between 2010 and 2015 will be 80.1 and 84.5, respectively. These would increase to 85.6 and 89.3 years respectively for those born between 2045 and 2050. The median age of the Singapore population would climb from 40 years in 2015 to 47 years in 2030 and 52.8 years in 2050. The break down of the males and females according to their ages as shown in the image below shows a clearer picture of the ageing crisis in Singapore.



This would mean that the dependency ratio will be halved to almost 1:1, with one adult supporting a child or an older adult. In 2015, there were 100 adults – persons aged 20 to 64 years – supporting about 50 children and elderly persons. However, by 2050, 100 adults would have to support about 95 children and elderly persons.

Ageing and the resources strain that comes along with it is a concern prevailing for ages, as such what could be done to change/improve this state?
You are required to build a model with the Lego bricks provided by expressing your solution about this building challenge.

Upon building give a description of your model below.

Air Pollution

As economies and carbon footprints grow, urbanisation accelerates, and global temperatures rise, our air quality deteriorates. Generally termed as climate change. Pollution may seem like an environmental problem, but, according to the World Health Organisation (WHO), there are severe health implications. As of 15th May 2019, Mexico City had declared an environmental emergency due to forest fires. The visual severity is shown in the image below.

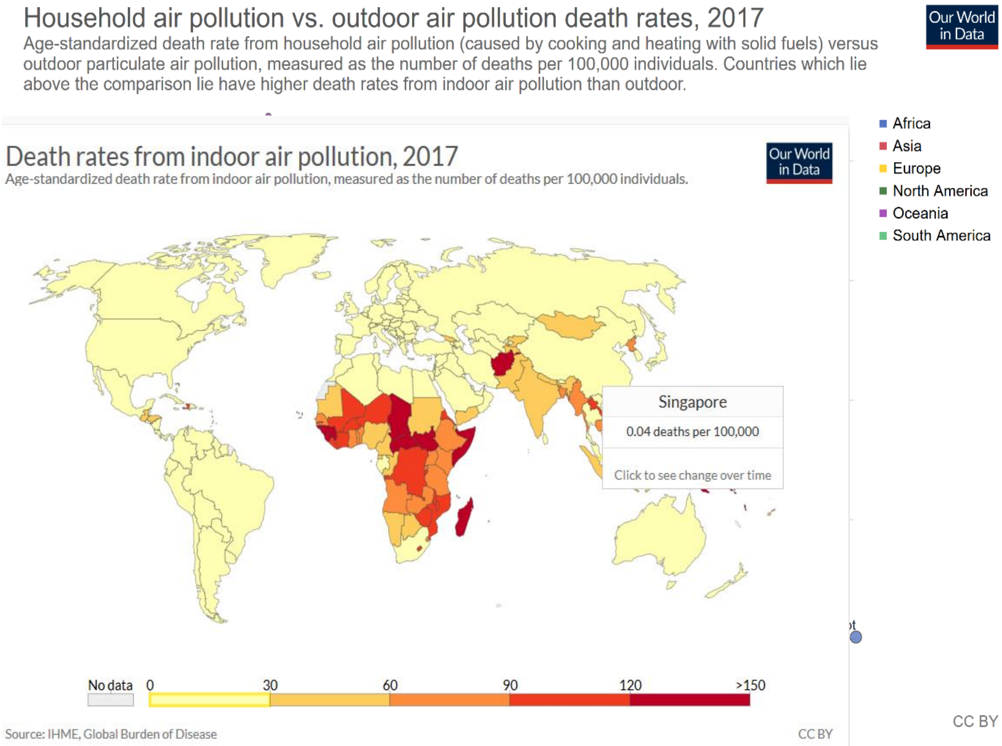
Source: Mexico from a drone, tweet from Santiago Arau

Each year, more than 400,000 Europeans die prematurely as a consequence of poor air quality, and many more suffer from respiratory and cardiovascular diseases caused by air pollution. Around 7 million people die every year from exposure to fine particles in polluted air that penetrate deep into the lungs and cardiovascular system, causing diseases including stroke, heart disease, lung cancer, chronic obstructive pulmonary diseases and respiratory infections, including pneumonia. In economic terms, bad air quality costs over €20bn a year to the European economy, due to increased medical costs and reduced worker productivity.

Ambient air pollution alone caused some 4.2 million deaths in 2016, while household air pollution from cooking with polluting fuels and technologies caused an estimated 3.8 million deaths in the same period. More than 90% of air pollution-related deaths occur in low- and middle-income countries, mainly in Asia and Africa as shown in the image below, followed by low- and middle-income countries of the Eastern Mediterranean region, Europe and America.

WHO recognises that air pollution is a critical risk factor for noncommunicable diseases (NCDs), causing an estimated one-quarter (24%) of all adult deaths from heart disease, 25% from stroke, 43% from chronic obstructive pulmonary disease and 29% from lung cancer.

Indoor air pollution is one of the world's most significant environmental



problems. Based on figures from the Institute for Health Metrics and Evaluation (IHME), 2.6 million people died prematurely in 2016 from illness attributable to household air pollution. It is predominantly women and young children who are killed by indoor air pollution.

The chart below shows death rates from indoor air pollution plotted against rates from outdoor particulate air pollution. Countries which lie above this line have higher death rates from indoor pollution relative to outdoor. Here we see that for a large number of countries, indoor air pollution is still dominant.

Under the blanket for climate change, air pollution has a detrimental effect on our health without us knowing it. As such, what could be done to change/improve this state?

You are required to build a model with the lego bricks provided by expressing your solution about this building challenge.

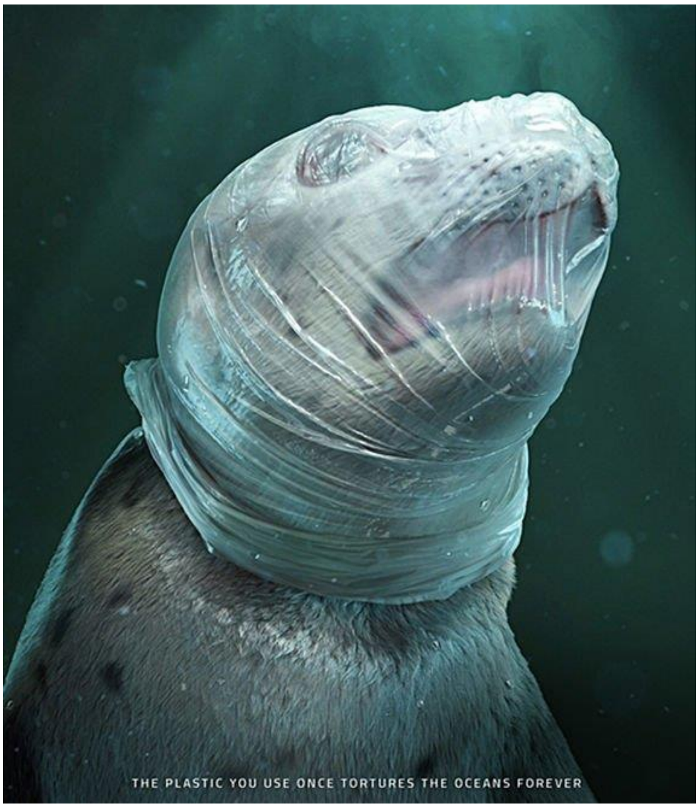
Upon building a short description of your model below.

Biodiversity

Biodiversity is under serious threat as a result of human activities population growth and resource consumption, climate change and global warming, habitat conversion and urbanisation, over-exploitation of natural resources and environmental degradation. UN scientists warn that roughly 1 million plant and animal species are on the verge of extinction due to human activity. It would be the first mass extinction since humans started walking the earth and have dire implications for the survival of our species.

Most of our planet is covered in water. We depend on the oceans to maintain our rainwater system and many populations rely on it for food and income. Oceans also absorb carbon dioxide and produce about 30% of our oxygen. Despite its importance, the ocean is under threat. Overfishing and unsustainable fishing practices are causing the endangerment and extinction of many fish species. Species began going extinct at a much faster pace. Over the past five centuries, researchers have recorded 514 animal extinctions on land. Before 1500, a few species of seabirds are known to have vanished. Since then, scientists have documented only 15 ocean extinctions, including animals such as the Caribbean monk seal and the Steller's sea cow. While these figures are likely underestimated.

The pictures show the reliance and the number of pollutants we produce every day to sustain our survival. One-time use waste being irresponsibly bumped into the oceans in the form of disposal is one of the main reasons for escalating extinction in recent year, as shown in the picture below.



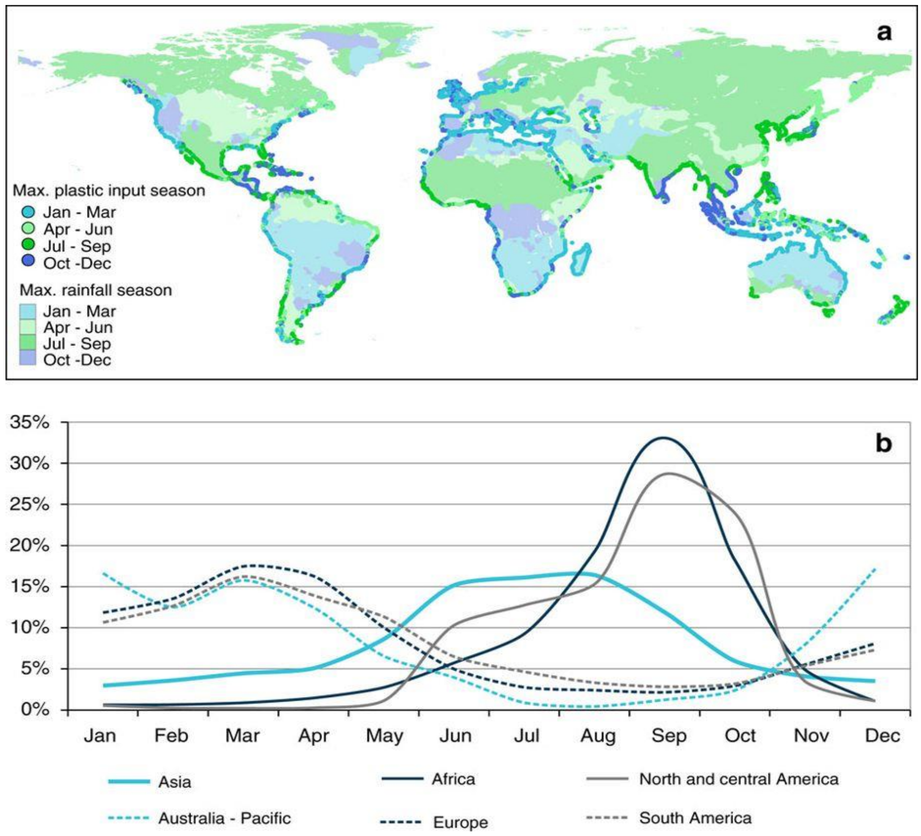
The table below provides a list of country that produces a high volume of plastic waste. Which also means how much of such non-biodegradable products we produce every day to meet the growing population needs.

From: River plastic emissions to the world's oceans

Catchment	Country	Lower mass input estimate (t yr^{-1})	Midpoint mass input estimate (t yr^{-1})	Upper mass input estimate (t yr^{-1})	Total catchment surface area (km^2)[21]	Yearly average discharge (m^3 s^{-1})[21]
Yangtze	China	3.10×10^5	3.33×10^5	4.80×10^5	1.91×10^6	1.58×10^4
Ganges	India, Bangladesh	1.05×10^5	1.15×10^5	1.72×10^5	1.57×10^6	2.08×10^4
Xi	China	6.46×10^4	7.39×10^4	1.14×10^5	3.89×10^5	5.53×10^3
Huangpu	China	3.35×10^4	4.08×10^4	6.73×10^4	2.62×10^4	4.04×10^2
Cross	Nigeria, Cameroon	3.38×10^4	4.03×10^4	6.5×10^4	2.38×10^3	2.40×10^2
Brantas	Indonesia	3.23×10^4	3.89×10^4	6.37×10^4	1.11×10^4	8.18×10^2
Amazon	Brazil, Peru, Columbia, Ecuador	3.22×10^4	3.89×10^4	6.38×10^4	5.91×10^6	1.40×10^5
Pasig	Philippines	3.21×10^4	3.88×10^4	6.37×10^4	4.07×10^3	2.07×10^2
Irrawaddy	Myanmar	2.97×10^4	3.53×10^4	5.69×10^4	3.77×10^5	5.49×10^3
Solo	Indonesia	2.65×10^4	3.25×10^4	5.41×10^4	1.58×10^4	7.46×10^2
Mekong	Thailand, Cambodia, Laos, China, Myanmar, Vietnam	1.88×10^4	2.28×10^4	3.76×10^4	7.74×10^5	6.01×10^3
Imo	Nigeria	1.75×10^4	2.15×10^4	3.61×10^4	7.92×10^3	2.79×10^2
Dong	China	1.57×10^4	1.91×10^4	3.17×10^4	3.33×10^4	8.54×10^2
Serayu	Indonesia	1.33×10^4	1.71×10^4	2.99×10^4	3.71×10^3	3.70×10^2
Magdalena	Colombia	1.29×10^4	1.67×10^4	2.95×10^4	2.61×10^5	5.93×10^3
Tamsui	Taiwan	1.16×10^4	1.47×10^4	2.54×10^4	2.68×10^3	1.08×10^2
Zhujiang	China	1.09×10^4	1.36×10^4	2.31×10^4	4.01×10^3	1.33×10^2
Hanjiang	China	1.03×10^4	1.29×10^4	2.19×10^4	2.95×10^4	7.35×10^2
Progo	Indonesia	9.80×10^4	1.28×10^4	2.29×10^4	2.24×10^3	2.79×10^2
Kwa Ibo	Nigeria	9.29×10^4	1.19×10^4	2.08×10^4	3.63×10^3	1.92×10^2

Input rate estimates (in t yr^{-1}) are representative of mismanaged plastic waste (MPW) production and catchment runoff. A lower, midpoint and upper estimate is calculated based on three regression analyses accounting for uncertainties in our field observations data set.

A study in California was the first to report levels of micro-plastics in river surface waters, with sampling in Los Angeles River, San Gabriel River and tributary Coyote Creek. The report found substantial temporal variations in plastic contamination levels. For a given location, the study found up to three orders of magnitude differences between plastic concentrations measured at different periods. These variations were mostly explained by events of dry and wet weather, implying that runoff plays an essential role in the transport of plastics into freshwater systems. In recent years, more studies sampled plastic in surface waters of rivers. In Europe, studies estimated that the Danube River releases 530–1,500 tonnes of plastic into the Black Sea annually. Another European study estimated that 20–31 tonnes flow into the North Sea every year from the Rhine River, with different locations along this river demonstrating the presence of significant sources (for example, wastewater treatment plants, tributaries) and sinks. In the Italian Po River, sampled concentrations differed by one order of



magnitude between winter and spring, emphasising seasonality of freshwater contamination in rivers.

a) River outflow locations are indicated by trimester period when respective peak input occurs. Peak seasons for precipitation rates from GLDAS are mapped on the continental landmass, showing a clear correlation with our predicted inputs. (**b**) Relative seasonality of plastic inputs from rivers into the ocean by continents. Continental contributions are expressed in percentage of respective annual mass inputs.

Global estimate of plastic emissions from rivers into the world's oceans: between 1.15 and 2.41 million tonnes per year. Most of this river plastic input is coming from Asia, which emphasises the need to focus on monitoring and mitigation efforts in Asian countries with rapid economic development and poor waste management. Research on freshwater plastic pollution is a relatively new field, and most efforts have been carried out in industrialised countries of Europe and North America. While many indicators suggest a dominant contribution of plastics from Asian countries, there is very little data to document these assumptions and thoroughly verify the validity of our model. The relatively high concentrations of ocean plastic found at the surface of the North Pacific Ocean where buoyant plastics originating from Asia suggests that our assumptions are plausible.

The impact of human activities had caused a detrimental effect on biodiversity more significantly with plastics and its usages. As such, what could be done to change/improve this state?

You are required to build a model with the lego bricks provided by expressing your solution about this building challenge.

Upon building give a description of your model below.

Appendix D: Scoring Rubrics

Point 1: Originality

	Usual Uses	Unusual Uses
Score	1	2

Please refer to the 'Usual Uses' tab to find out the usual uses of the individual scenario

Point 2: Fluency

	Elaboration	No Elaboration
Score	1	0

*Plagiarism, -1

Please make the description of the model follows the following guidelines before scoring,

1. Description is being link
back to the scenario

2. Description of the lego model built
(Description must be at least 70% done for the model; Description being link to the model)

3. Explanation of the lego model built
(e.g. When/Where/How does the model is being utilise; Feasibility; Specificity)

Point 3: Build

	Sophisticated Build	Normal Build	No Build
Score	2	1	0

*Plagiarism, -1

Please refer to the following guidelines,

1. Aesthetic; Colour coordination

2. Creative usage of the lego bricks

3. Amount of effort

4. Complexity

Appendix E: Usual Uses

Climate Change

Solar panels
Windmill
3 Rs (Reuse, Reduce, Recycle)
Policy
Industrial Uses
Education
Trees
Plantation
Green building
Tidal energy
Vehicles

Poverty

Basic Metaphor (e.g Bridges which connect the poor and rich)
Homeless people
Schools
Policy
Money
Houses
Education

Mental Health

Companion robots
Companion
Education
Counsellors
Hospital/Clinics

Ageing Population

Committee Centres
Policy
Elderly Care
Education
Elderly friendly amenities
Facilities

Air Pollution

Air purifier
Solar panels
Windmill
3 Rs (Reuse, Reduce, Recycle)
Trees
Plantation
Green building
Vehicles
Filters
Cooking fuels
Education
Policy
Industrial Uses

Biodiversity

3 Rs (Reuse, Reduce, Recycle)
Plastic pollution
Collecting sea plastic
Policy
Education

Appendix G: Preprocess EEG Signals MATLAB Codes

```
rawDataFiles = dir('*.edf');
   for subjID = 1:length(rawData)
      loadName = rawDataFiles(subjID).name;
      dataName = loadName(1:end-4);
      EEG = pop_biosig(loadName);
      fprintf(loadName)
      EEG.setname = dataName;
   try
      EEG = pop_select( EEG, 'channel',{'AF3','F7','F3','FC5','T7','P7','O1','O2','P8','T8','FC6','F4','F8','AF4'});
      EEG = pop_chanedit(EEG, 'load','D:\14emotiv.ced','filetype','autodetect');
      EEG = pop_clean_rawdata(EEG, 'FlatlineCriterion','off','ChannelCriterion','off','LineNoiseCriterion','off','Highpass',[0.75 1.25] ,'BurstCriterion',10,'WindowCriterion',0.25,'BurstRejection','off','Distance','Euclidian','WindowCriterionTolerances',[-Inf 7] );

      EEG = pop_reref(EEG, []);
      EEG = pop_rmbase( EEG, [],[]);
      EEG = pop_runica(EEG, 'icatype', 'runica', 'extended',1,'interrupt','off');
      EEG = eeg_checkset(EEG, 'ica');
      EEG = pop_reref(EEG, []);
      EEG = pop_iclabel(EEG, 'default');
      EEG = pop_icflag(EEG, [NaN NaN;0.9 1;0.9 1;NaN NaN;NaN NaN;NaN NaN;NaN NaN]);

      EEG = eeg_regepochs(EEG, 'recurrence', 2, 'limits', [0,2]);
```

```
        EEG = pop_eegthresh(EEG, 1, (1:14), -100, 100, 0, 2, 0, 1);


        EEG = pop_eegfiltnew(EEG, 'hicutoff',30);
        EEG = pop_rmbase( EEG, [],[]);
        EEG = pop_runica(EEG, 'icatype', 'runica', 'extended',1,'interrupt','on');
        EEG = eeg_checkset(EEG, 'ica');
        EEG = pop_reref(EEG, []);
 catch ME
     fprintf('Not successful: %s\n' , ME.message);
     continue;
    end
          EEG = pop_saveset(EEG, 'filename', dataName, 'filepath','C:\Users\Shmitha\Desktop\rd1');


    end
```

7.4.1 Calculation for power spectral density

```
rawData = cd('C:\Users\Shmitha\Desktop\test');
rawDataFiles = dir('*.set');
Round1 = table;
for subjID = 1:length(rawData)
     loadName = rawDataFiles(subjID).name;
     EEG = pop_loadset(loadName);
      x = string(loadName);
      for chanNr = 1:length(EEG.chanlocs)
            [spectra,freqs] = spectopo(EEG.data(chanNr,:), 0, EEG.srate,'plot','off');


            % delta=1-4, theta=4-8, alpha=8-13, beta=13-30
            deltaIdx = find(freqs>1 & freqs<4);
            thetaIdx = find(freqs>4 & freqs<8);
            alphaIdx = find(freqs>8 & freqs<13);
```

```
        betaIdx  = find(freqs>13 & freqs<30);

        % compute absolute power
        deltaPower = mean(10.^(spectra(deltaIdx)/10));
        thetaPower = mean(10.^(spectra(thetaIdx)/10));
        alphaPower = mean(10.^(spectra(alphaIdx)/10));
        betaPower  = mean(10.^(spectra(betaIdx)/10));

    y = table(x,chanNr,deltaPower,thetaPower,alphaPower,betaPower);
    Round1 = [Round1; y];
    end
end
pop_topoplot(Round1, EEG.chanlocs)
```

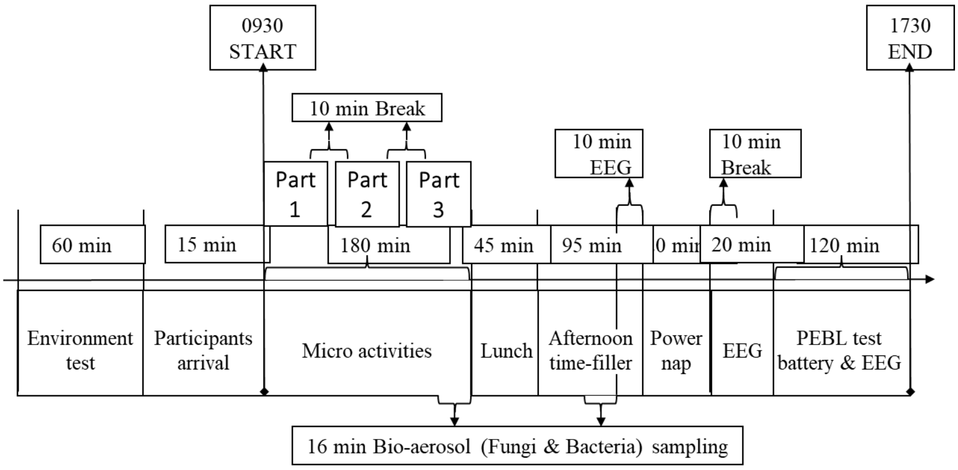
Appendix H: IRB Documents

Sample schedules for each group of participants

Schedule 1

Day	Indoor air quality conditions
1	Reduced ventilation rate -0.5 ACH
2	Reduced ventilation rate -0.5 ACH
3	Lowered PM 2.5 levels - 1 ACH
4	Lowered CO2 levels- 1 ACH
5	Lowered VOC level - 1 ACH
6	Lowered VOC and PM2.5 levels - 1 ACH

Participant protocol



Week 0							Week 1							Week 2							Week 3							Week 4							Week 5							Week 6						
T	**F**	S	S	M	T	W	T	**F**	S	S	M	T	W	T	**F**	S	S	M	T	W	T	**F**	S	S	M	T	W	T	**F**	S	S	M	T	W	T	**F**	S	S	M	T	W	T	**F**	S	S	M	T	W
	A	B	C	D	E	F		A	B	C	D	E	F		A	B	C	D	E	F		A	B	C	D	E	F		A	B	C	D	E	F		A	B	C	D	E	F		A	B	C	D	E	F

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Consent to Participate in IAQ-Regulated Experiment for Cognitive Performance Test

Title of study: Indoor Air Quality and Cognitive Performance

Investigators:

Name:	A/P Wan Man Pun	**Dept:**	MAE	**Contact:**	mpwan@ntu.edu.sg (6790 5498)
Name:	Asst/P Ng Bing Feng	**Dept:**	MAE	**Contact:**	bingfeng@ntu.edu.sg (6790 4163)
Name:	Prof Soh Chee Kiong	**Dept:**	CEE	**Contact:**	CSOHCK@ntu.edu.sg
Name:	Dr. Roberts Adam Charles	**Dept:**	MAE	**Contact:**	AROBERTS@ntu.edu.sg
Name:	Miss Shmitha D/O Arikrishnan	**Dept:**	IGS/ERI@N	**Contact:**	shmithad001@e.ntu.edu.sg

Introduction
- You are being asked to be in a research study of assessing the impacts of indoor air quality (IAQ) on the cognitive performance of adults living in Singapore. You will join in a neuropsychological test subject to different aspects of office environment.
- Eligible participants are university students and research staffs above 18 years old.
- We ask that you read this document and raise any questions that you may have before agreeing to be part of the study.

Purpose of Study
- The purpose of the study is to establish the link between IAQ and the cognitive performance among adults living in Singapore.

Description of the Study Procedures
If you agree to be in this study, you will be tasked with the following:
- Stay within the designated room (N1.1-B5M-02) from 9:30AM to 5:30PM for 7 weeks over the same given day;
- Perform normal activities (e.g., typing, reading, etc.) during the test;
- Take a series of computerized questionnaires while spending time in the room;
- Undertake simple and non-invasive measurement of physiological signals using well tested and documented commercial instruments. These include instruments to measure finger skin temperature, heart rate, blood pressure and electroencephalograph (EEG)[1].

IAQ within the Code of practice for indoor air quality for air-conditioned buildings (SS554) issued by Spring Singapore. Using the code as a guideline, test will be carried out to the test different aspects of office environment while modifying certain aspects over the course of time such as thermal comfort, IAQ, number of occupants, glare etc.

The impact of IAQ on cognitive functioning will be correlated through subsequent statistical analysis and the collected data will be adjusted for different patterns of participant well-being, age, gender, medical history, etc.

Risks/Discomforts of Being in this Study
- There are no reasonably foreseeable (or expected) risks.
- You declare to be healthy and any prior medical conditions must be made known to the investigators at the beginning of the study.
- At any point in the study, should you feel discomfort, you are free to withdraw as a participant without penalty.

Benefits of Being in the Study
- The participant will get the chance to understand and train their cerebrum.

- Free lunch
- Hands on experience with EEG

Confidentiality

- You agree to have the results of your cognitive performance recorded as part of the study.
- The personal particulars of participants in this study will be kept strictly confidential
- In reports and publications, we will not include information that would possibly identify as a participant of the study.

Sharing of Information

- As a participant, you will not share results or information from the study to any individuals who are not involved.

Photography/Video/Audio Recordings

- You grant the investigators the full rights to use the images resulting from the photography/video filming, and any reproductions or adaptations of the images for presentation, publicity, in reports to funding bodies or other purposes to help achieve the investigating team's aims. This might include (but is not limited to), the right to use them in their printed and online publicity, social media, press releases and funding applications.
- Participant may revoke this authorization at any time by notifying to the investigating team in writing. The revocation will not affect any actions taken before the receipt of this written notification.
- Images will be stored in a secure location and only authorized staff will have access to them. They will be kept till it is relevant and after that time destroyed or archived.

Payments

- Each participant will be paid S$ 420 (excluding lunch) for the time spent in participation over the stated duration of this study.
- Participants must complete the full duration (9:30AM to 5:30PM over 7 weeks) before reimbursement is made through NTU finance. There will be no partial payment if participants withdraw before or during the experiment or are missing for a substantial period (15 minutes and more) during any point in time of the study.

Right to Ask Questions and Report Concerns

You have the right to ask questions about this research study and to have those questions answered by me before or after the course of the study. If you have any further questions about the study, at any time feel free to contact Miss Shmitha D/O Arikrishnan (shmithad001@e.ntu.edu.sg). Alternatively, you may also contact NTU-Institutional Review Board (IRB) for information on ethics and your rights as a participant. The contact details of IRB are as follow: IRB-2017-06-014
Email: irb@ntu.edu.sg
Tel: +65 6592 2495

Consent

- Your signature below indicates that you have agreed to the terms of condition to volunteer as a research participant for this study, and that you have read and understood all the information provided above.

Subject's Name : ______________________________

Subject's Signature: ______________________________ Date: ________________

Investigator's Signature: ______________________________ Date: ________________

[1] The EEG device passively measures the brain wave of synaptic, receptor and active potentials on surface of the human body. These measurements do not alter or introduce any form of interferences to the subject's well-being or health i.e. picks up electrical signals on the surface that is generated by the brain itself and is non-invasive.

Personal Particulars

Name: ___________

Gender: ☐ Female ☐ Male

Date of birth: ___________

Address: ____

Nationality: _____________

Ethnic origin: ___________________________

Telephone: (home) ___________ (hp) ___________

Please select your education level and also your matric number by the side:
☐ Bachelor ☐ Master ☐ PhD

Are you currently *(check only one)*:
☐ Married ☐ Single ☐ Separated ☐ Divorced ☐ Widowed

List Languages spoken/written:

____

Colour Blind? If so state which colours

____

Medical History

1. Are you having flue/cold symptoms?
☐ Yes ☐ No

2. Do you have claustrophobia?
☐ Yes ☐ No

3. Please indicate below which chronic condition(s) you have:
☐ Diabetes ☐ Asthma ☐ Emphysema or COPD
☐ Other lung disease *Type of lung disease:* ________________________
☐ Heart disease *Type of heart disease:* ________________________
☐ Arthritis or other rheumatic disease *Specify type:* ________________________
☐ Cancer *Type of cancer:* ________________________
☐ Other chronic condition *Specify:* ________________________

4. **In the past 6 months**, how many times did you visit a physician? _______ visits
Do not include visits while in the hospital or the hospital emergency department.

5. **In the past 6 months**, how many times did you go to a **hospital** emergency department? ______ times

6. **In the past 6 months**, how many TIMES were you hospitalized for one night or longer? _______ times

Confidence about Doing Things

For each of the following questions, please *circle* the number that corresponds with your **confidence** that you can do the tasks regularly at the present time.

How confident are you that you can...

1	Keep the fatigue caused by your disease from interfering with the things you want to do?	Not at all confident	1	2	3	4	5	6	7	8	9	10	Totally confident
2	Keep the physical discomfort or pain of your disease from interfering with the things you want to do?	Not at all confident	1	2	3	4	5	6	7	8	9	10	Totally confident
3	Keep the emotional distress caused by your disease from interfering with the things you want to do?	Not at all confident	1	2	3	4	5	6	7	8	9	10	Totally confident
4	Keep any other symptoms or health problems you have from interfering with the things you want to do?	Not at all confident	1	2	3	4	5	6	7	8	9	10	Totally confident
5	Do the different tasks and activities needed to manage your health condition so as to reduce your need to see a doctor?	Not at all confident	1	2	3	4	5	6	7	8	9	10	Totally confident
6	Do things other than just taking medication to reduce how much your illness affects your everyday life?	Not at all confident	1	2	3	4	5	6	7	8	9	10	Totally confident

General Health

In general, would you say your health is *(Circle one)*:

Excellent 1
Very good...............................2
Good.......................................3
Fair 4
Poor..5

Reference:

Sample Questionnaire – Chronic Disease (August 2007). Stanford Patient Education research centre, Stanford University School of Medicine. Available: *http://patienteducation.stanford.edu/research/cdquest.pdf*.

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