The Impact of Indoor Thermal Environments on the User's State of Mind in Educational Buildings in Auckland, New Zealand

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By

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Abstract

The impact of the built environment on the human state of mind is often neglected despite the ever-increasing demand for urbanized life and fast-constructed building. Nevertheless, the average time spent inside the built environment is 90% of the average lifespan. This significant amount of time forms an essential relationship between our occupants and the surroundings that justify our behaviour and impact our long-term psychological wellbeing.

This research aims to: Measure the impact of Indoor Air Quality (IAQ) and Thermal Comfort (TC) on the momentary state of mind (mood) of the participants in the educational building's using brain mapping Electro-Encephalography (EEG).

The impact of spaces on user's state of mind can be measured and analysed by the suitable brain mapping technology, i.e., EEG. This measurement of the impact on the human brain, even being momentary, will indicate the mental state (excited, engaged, relaxed, etc.) of the users while occupying certain space, in various indoor thermal settings. Hence it can be compared with the predetermined building function.

The study depends on user's surveys and experts' in-depth interviews, to set up the design function of the selected spaces (i.e., engagement, focus, excitement, etc.). This mixed method approach is to guarantee that user expectation, and the stakeholder's purpose, of educational buildings are consistent and benchmarked for the experiment. The results of the qualitative and quantitative data collection, after analysis, were used to set up the experiment stage. Based on these results we have identified the lecture room to be the most critical for the overall occupant's thermal perception and identified the occupant preferred state of mind that fulfil the building purpose.

The subjects of the experiments represent a diversity of all the possible users of the educational buildings and occupied the allocated spaces, wearing EEG scanner to measure the actual brain function recorded in deferent indoor thermal environments, measured by the Predictive Mean Vote (PMV). The study depends on two experiments to identify the impact of two parameters, out of four, of IEQ (Indoor Air Quality and Indoor Thermal Comfort). The results, of each experiment, analysed against the predetermined design purpose.

This research provides important insights into the neurological mechanisms underlying thermal comfort, which have ramifications for the design and management of indoor environments in educational buildings. We can better understand how environmental factors such as temperature and ventilation affect the occupants' brain and ultimately impact the occupant's state of mind by using EEG to investigate the neural correlates of thermal comfort.

The research showed, in all stages, the significance of ITC on the occupant performance in educational building. The measured brain waves indicated that the occupant's performance is significantly improved in PMV range between 0 to 0.6 and during open ventilation. This research results are critical to optimise the thermal performance in educational building and creating a better indoor environment for the building users.

Table of Contents

List of Figures

List of Tables

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Sameh Azzazy

30/09/2023

List of publications

1. Sameh Azzazy, Amirhosein Ghaffarianhoseini, Ali GhaffarianHoseini, Nicola Naismith and Zohreh Doborjeh (2021). A critical review on the impact of built environment on users' measured brain activity, Architectural Science Review, 64:4, 319-335, DOI: 10.1080/00038628.2020.1749980

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2. Sameh Azzazy, Amirhosein Ghaffarianhoseini, Ali GhaffarianHoseini, Nicola Naismith and Hossein Omrany (2020). The brain response to indoor thermal comfort: from the thermal perception to the current indoor thermal comfort indices.

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3. Sameh Azzazy, Amirhosein Ghaffarianhoseini, Ali GhaffarianHoseini, Nicola Naismith, Dat Tien Doan and Justin B. Hollander (2023). The perception of Indoor Thermal Comfort: in educational buildings in Auckland, New Zealand.

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4. Sameh Azzazy, Amirhosein Ghaffarianhoseini, Ali GhaffarianHoseini, Nicola Naismith and Zohreh Doborjeh (2023). The impact of Indoor Thermal Comfort on the occupant performance: in educational buildings in Auckland, New Zealand, measured by EEG.

   Awaiting submission – Chapter 5

Co-Authored Works and Declaration of Collaboration

Statement from co-authors confirming the authorship contribution of the PhD candidate:

As co-authors of the research the above-mentioned publications, we confirm that Mr. Sameh Azzazy contributed over 80% of the research. Mr. Sameh Azzazy is responsible for writing, ideas, and the content of the research.

Supervisors, Dr Amirhosein Ghaffarianhoseini, Dr Ali GhaffarianHoseini and Prof. Nicola Naismith, provided guidance and support to improve the quality of the research.

Subject experts, Dr Zohreh Doborjeh, Dr Hossein Omrany, Dr Dat Tien Doan and Dr Justin B. Hollander, provided their expertise and advice as subject experts to support the research.

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Chapter 1 – Introduction

1.1 Background

The rapid urban growth projected for the year 2050 indicates that a significant portion of the global population, approximately two-thirds, will reside in cities or urban areas (Y. Zhou, Varquez, and Kanda, 2019). Accordingly, more than two billion people will be accommodated in new buildings added to the current urban landscape. By 2030 the urban developed land is expected to increase by more than one million Km^2 (Goldhagen, 2017; Seto, Fragkias, Güneralp, and Reilly, 2011). Despite this trend, the influence of the built environment on human well-being is often overlooked due to the prevailing demand for expedited construction. However, it is crucial to recognize that individuals spend approximately 90% of their lives inside built environments (Evans and McCoy, 1998; Hillier and Hanson, 1989; Stamper et al., 2016), This portion forms an essential relationship between our inner self and the surrounding that justify our behaviour (Ellard, 2015; Proulx, Todorov, Taylor Aiken, and de Sousa, 2016).

As the role of the built environment in shaping occupants' experiences gains prominence, the connection between indoor thermal comfort and occupant performance emerges as a significant subject. Previous research has illuminated the intricate interplay between indoor thermal conditions and cognitive functions (Azzazy, Ghaffarianhoseini, GhaffarianHoseini, Naismith, and Doborjeh, 2020). The brain's response to temperature fluctuations highlights a dynamic yet underexplored avenue for understanding how thermal comfort can bolster or hinder occupants' cognitive abilities. This study aims to delve deeper into this complex relationship by examining the influence of indoor thermal comfort on occupants' cognitive performance. By unravelling the underlying mechanisms and quantifiable effects, this research seeks to illuminate a vital aspect of indoor environments that can profoundly impact occupants' engagement, productivity, and overall well-being.

In recent years, there has been a surge of scientific interest in exploring the concept of a healthy built environment and its impact on physical well-being. Nonetheless, the investigation into the effects of the built environment on psychological well-being and subjective experiences remains inadequate.

1.2 Research Challenge

Psychological well-being and occupants’ metal state encompass various aspects, including hedonic, eudaimonic, and even physical elements (Ryan and Deci, 2001; Ryff, Singer, and Dienberg Love, 2004; Sheldon, Corcoran, and Prentice, 2018). Within the context of indoor environments, occupants perceive their surroundings through neural channels, connecting sensory receptors to the brain. Among these perceptions, indoor thermal comfort (ITC) plays a distinct role in shaping individuals' mental states, ranging from unconscious thermoregulation to conscious behaviours (Aizawa et al., 2019). The aim of this study is to critically review existing theories of ITC and its correlation with occupants' perceptions, as well as to examine its impact on their performance in fulfilling the intended functions of the built environment.

The complexity of the relationship between occupants and the built environment poses challenges for empirical research. The intricate interconnectivity between neural receptors and the surrounding environment adds complexity, as certain stimuli (e.g., shapes or colours) can trigger diverse memories and emotions that are imperceptible when humans serve as experimental subjects. Consequently, comprehensive methodologies are essential in empirical studies to identify the influence of thermal alterations on occupants' brains (Azzazy et al., 2020; Coburn, Vartanian, and Chatterjee, 2017). Therefore, the research methodology encompasses several stages, including surveys, interviews, experiments, and comprehensive data analysis.

In conducting this study, it is essential to acknowledge that we are among the very first researchers to focus on the specific topic of indoor thermal comfort (ITC) and its correlation with occupants' perceptions in the context of indoor environments in New Zealand. While the field of psychological well-being and its connection to indoor environments has been a subject of interest for researchers globally, there has been limited attention given to the unique aspects of ITC in New Zealand.

Highlighting the importance of this research, understanding the relationship between indoor thermal comfort and occupants' mental states is crucial for several reasons. Firstly, psychological well-being is a fundamental aspect of human health and productivity. By investigating the impact of thermal comfort on individuals' mental states, we can gain insights into how indoor environments can be optimized to enhance occupants' overall well-being, satisfaction, and performance.

Secondly, New Zealand's diverse climate and architectural styles make it a unique setting to explore the interplay between indoor thermal conditions and occupants' experiences. The country's temperate maritime climate and increasing awareness of sustainable building practices necessitate a thorough investigation of ITC, as it directly influences the comfort and energy efficiency of indoor spaces.

Thirdly, with the ongoing global focus on sustainability and energy conservation, understanding the psychological aspects of indoor thermal comfort can provide valuable information for designing energy-efficient buildings without compromising occupants' comfort and well-being.

Moreover, the complexity of the relationship between occupants and the built environment, as mentioned earlier, further emphasizes the need for dedicated research in this area. The neural pathways connecting sensory receptors to the brain and their influence on perceptions and emotions create a challenging and dynamic landscape for empirical investigations.

The Multifaceted Nature of Psychological Well-being

Psychological well-being, an intricate amalgamation of hedonic, eudaimonic, and even physiological dimensions, engages with indoor environments through neural pathways, channelling sensory stimuli to the brain. Among these perceptive processes, indoor thermal comfort (ITC) assumes a pivotal role in sculpting individuals' mental states, ranging from unconscious thermoregulation to overt behaviours. In this vein, the present study endeavours to examine prevailing ITC theories, explain their interplay with occupants' perceptions, and decode their influence on accomplishing the intended functional roles of built environments.

The Performance Nexus: Linking Thermal Comfort and Occupant Performance

Indoor thermal comfort is not a mere matter of physical comfort; it intricately entwines with occupants' cognitive and physiological domains, which, in turn, extend to their performance. Emerging studies highlight the pivotal role of indoor thermal conditions in shaping occupants' cognitive function, concentration, and overall performance (Guevara, Soriano, and Mino-Rodriguez, 2021; J. Li, Yu, Haghighat, and Zhang, 2019b). Cognitive psychology unveils the intricate connections between thermal comfort and information processing, suggesting that optimal indoor thermal conditions can bolster cognitive performance, problem-solving abilities, and decision-making processes. The study at hand aims to explore the underpinning mechanisms and quantifiable impacts of indoor thermal comfort on occupant performance, thus enhancing the comprehension of how the built environment fundamentally influences human efficiency and efficacy.

By employing comprehensive methodologies encompassing surveys, interviews, experiments, and advanced data analysis techniques, this research aims to fill the existing knowledge gaps and shed light on the intricate interplay between indoor thermal comfort, psychological well-being, and the functionality of indoor spaces in New Zealand.

Overall, this study seeks to contribute to the growing body of knowledge on the psychological aspects of indoor environments and ITC, paving the way for informed design strategies and policies that foster healthier, more comfortable, and productive built environments in New Zealand and beyond.

1.2 Current Gap

Given the complexity and limited maturity of the subject, two comprehensive literature reviews were conducted. The first review, presented in Chapter 2, examines research efforts investigating the impact of the built environment on individuals' mental states, focusing on brain activity measurements as indicators. The reviewed literature reveals that natural environments elicit more disentangled and meditative brain activities, while built environments tend to induce higher levels of stress. However, the mechanisms through which the built environment affects the brain remain inadequately explored. This review identifies current gaps and serves as a foundation for shaping future research towards the development of a restorative built environment that maximizes user well-being.

Only 87 papers in the literature were found to be related to the subject, with only 52 original research studies focusing on buildings and the built environment (Aspinall, Mavros, Coyne, and Roe, 2015; Banaei, Hatami, Yazdanfar, and Gramann, 2017; Gidlow et al., 2016; Hollander and Foster, 2016; Karandinou and Turner, 2018; Valtchanov and Ellard, 2015). Surprisingly, 69% of these publications originated from non-engineering or non-built environment-related journals, indicating a significant research shortage in the development process of the built environment. Moreover, the majority of the reviewed studies utilized social and psychological analyses rather than scientific instrument measurements, such as brain scanning (Banaei, Yazdanfar, Nooreddin, and Yoonessi, 2015; Shemesh et al., 2016; Tang et al., 2017), to investigate the impact of the built environment on the human brain.

The second literature review, presented in Chapter 2, narrows the research focus to ITC. Brain mapping studies were analyzed to determine the significance of ITC in occupants' brains. The findings demonstrate that thermal variations affect six brain regions, highlighting the influence of the thermal environment on individuals' mental states. Moreover, the results indicate that current thermal indices inadequately account for the neuropsychological effects of thermal sensation, thereby limiting their ability to comprehensively assess perceived thermal comfort (PTC).

Building Assessment Indices: Filling the Gaps

The evolution of sustainable building assessment frameworks, such as LEED, BREEAM, and Green Star, marks a pivotal milestone in promoting environmentally conscious and energy-efficient design. However, a noticeable gap remains in these indices concerning their inadequate incorporation of the intricate psychological dimensions of indoor environments. While energy efficiency and environmental sustainability stand as critical benchmarks, the profound effects of indoor thermal comfort on occupants' mental states and performance often remain relegated to the periphery. This research embarks on addressing this gap by advocating for a comprehensive overhaul of these indices. By integrating occupants' psychological well-being and cognitive performance as core evaluation criteria, the reimagined indices can pave the way for more holistic, human-centric building design and operation, ushering in a new era of indoor environments that genuinely prioritize occupants' overall satisfaction and productivity.

The Limitations of Conventional Indices

While these indices offer comprehensive frameworks for assessing buildings' environmental attributes, they tend to fall short in accounting for the nuanced psychological impacts of indoor thermal comfort. Conventional indices often rely on standardized metrics that lack the granularity to capture the intricacies of occupants' thermal experiences and their subsequent influence on cognitive states and performance. The omission of these dimensions underscores a critical gap in building assessment frameworks.

Addressing the Gap: A Call for Comprehensive Indices

Recognizing this gap, the present study underscores the necessity of incorporating indoor thermal comfort as a pivotal criterion within building assessment indices. By integrating occupants' psychological well-being, cognitive performance, and subjective thermal experiences, future indices can offer a more holistic evaluation of indoor environments. This proactive approach ensures that the psychological dimensions of indoor thermal comfort are systematically embedded within the evaluation process, guiding the creation of indoor spaces that prioritize both energy efficiency and occupant well-being.

1.3 Research objective

Research Statement:

The overarching aim of this thesis is to comprehensively examine the intricate relationship between indoor thermal comfort, occupant psychological states, and performance within educational buildings. By integrating theoretical frameworks, empirical studies, and advanced methodologies, this research seeks to illuminate the multifaceted dynamics shaping occupants' experiences in indoor environments, ultimately contributing to the design of healthier, more productive educational spaces.

Research Questions:

To guide our exploration, the following research questions serve as focal points across the chapters of this thesis:

- How does indoor thermal comfort influence occupants' psychological states and performance within educational buildings?
- What are the critical factors within educational buildings that significantly impact thermal comfort and preferred mental states conducive to improved performance?
- How can user experiences and preferences be aligned with stakeholder objectives to optimize indoor thermal conditions and enhance occupants' well-being and productivity?

Research Objective:

This research aims to investigate the complex interplay between indoor thermal comfort, occupant psychological states, and performance within educational buildings. By integrating theoretical insights, empirical studies, and stakeholder perspectives, the objective is to generate actionable recommendations for optimizing indoor environments to foster healthier, more productive learning and working environments. The objectives of this research are as follows:

- Identify and quantify the significance of ITC for the occupant's state of mind.
- Investigate and measure the impact of indoor thermal variation on occupants' state of mind and performance in educational buildings.
- Identify critical spaces within educational buildings that significantly influence thermal performance and preferred mental states conducive to improved performance.
- Bridge the gap between user expectations and stakeholder objectives by aligning user experiences and preferences with the design and operation of educational buildings.

And finally, provide recommendations and design guidelines to optimize indoor thermal conditions and enhance occupants' state of mind and performance in educational settings.

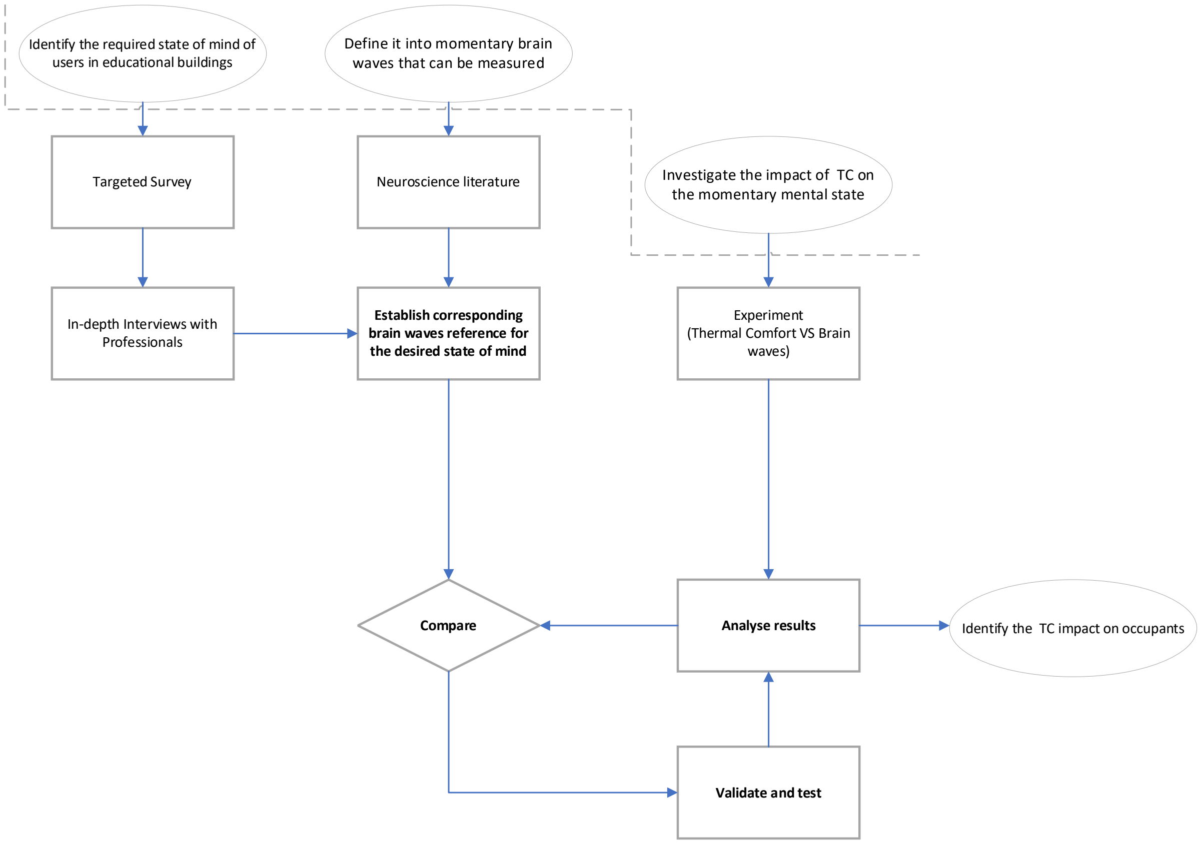
1.4 Methodology

Psychological analysis studies offer insights into long-term psychological well-being, while brain mapping relies on advanced scientific measurements but provides more momentary assessments. To isolate the impact of the built environment on the occupant performance, momentary measurements are considered more indicative. Previous studies in the literature have examined the relationship between indoor environmental quality (IEQ) and user comfort, primarily relying on psychological analyses. However, these studies have neglected to investigate the momentary mental state of users, which serves as the foundation for both comfort and productivity.

The objective of this research is to investigate the impact of indoor thermal variation on occupants' state of mind and performance in educational buildings. The study aims to provide insights into the relationship between indoor thermal conditions, occupant satisfaction, and performance, with a specific focus on creating optimal indoor environments in educational settings.

Therefore, this study employs a mixed-method approach, including user surveys and in-depth interviews with experts, to identify critical spaces in educational buildings that significantly influence thermal performance and preferred mental states (e.g., engagement, interest, focus) conducive to improved performance. By ensuring consistency between user expectations and stakeholder objectives in educational buildings, this approach aims to bridge the gap. Additionally, EEG recordings are used to measure the actual brain function of participants against controlled changes in predicted mean vote (PMV) as an indicator of thermal comfort.

1 Figure 1.1: Study method diagram, provides an overview of our methodology, which incorporates experimental, survey, interview, and literature review techniques. By adopting a multimodal approach, this study delves into the intricate aspects contributing to indoor thermal comfort by adopting a multimodal approach.



1 Figure 1.1: Study method diagram

To achieve these objectives, the research methodology consists of the following key components:

1. Literature Review: A comprehensive review of existing literature was conducted to establish a theoretical foundation and gain insights into the current understanding of indoor thermal comfort, occupant state of mind, and performance in educational buildings, Chapter 2 and 3.
2. Survey: Developing and administering a survey to a sample of participants to gather data on their experiences and perceptions of thermal comfort in indoor environments. The survey includes questions related to demographic information, thermal sensation, occupants' state of mind preferences and overall comfort level, Chapter 4.
3. In-Depth Interview: In-depth interviews were conducted with experts to gather detailed information and qualitative insights regarding the impact of indoor thermal conditions on occupant state of mind and performance and the current practices to achieve ITC. These interviews allowed for a deeper understanding of occupants' and stockholders' perception, beliefs, and experiences, Chapter 5.
4. Experiment: Controlled experiments were conducted in selected educational buildings, where participants were exposed to varying indoor thermal conditions. Advanced scientific measurements, i.e., EEG recordings, were used to assess participants' brain function and correlate it with the controlled changes in predicted mean vote (PMV) as an indicator of performance against thermal comfort, Chapter 5.
5. Analysis: The collected data from surveys, interviews, and experimental measurements were analysed using appropriate statistical techniques. Quantitative analysis involved descriptive statistics, correlation analysis, and regression analysis, while qualitative analysis focused on identifying recurring themes and patterns in the qualitative responses, Chapter 4 and 5.

1.5 Novelty

The significance of this research lies in its examination of building functionality based on users' measured experiences using brain mapping technology, an area that has received relatively less attention in the literature. The study specifically focuses on the impact of indoor environment quality (IEQ), particularly indoor air quality (IAQ) and indoor thermal comfort (ITC), on users' mental states. This novel attempt to assess functional buildings based on user-measured experiences via brain mapping (EEG) will contribute to the body of knowledge and promote the optimization of thermal performance in educational buildings, thereby creating better indoor environments for building occupants.

The pioneering nature of this research in New Zealand holds immense potential for advancing the understanding of indoor environmental quality (IEQ) and its impact on occupants' mental states. By utilizing brain mapping technology, specifically (EEG), to measure users' experiences, our study breaks new ground in the assessment of building functionality based on objective neurological data, which has been relatively unexplored in the existing literature. The use of EEG to evaluate the influence of indoor air quality (IAQ) and indoor thermal comfort (ITC) on users' mental states provides a powerful tool for gaining insights into the subconscious and conscious responses of building occupants to their surroundings. This innovative approach allows us to move beyond self-reporting and traditional survey methods, offering more accurate and reliable data on occupants' cognitive and emotional responses to indoor environments.

The significant impacts of this research extend to several key areas. Firstly, it can lead to a deeper understanding of how indoor environmental factors influence occupants' well-being, cognitive performance, and productivity. This knowledge is essential for architects, engineers, and building designers to create more human-centric and comfortable indoor spaces.

Secondly, the practical implications of our findings can directly benefit end-users, such as students and teachers in educational buildings. By optimizing thermal performance based on users' measured experiences, we can enhance the learning and working environments, promoting better concentration, focus, and overall satisfaction. Furthermore, our research can pave the way for the implementation of evidence-based design strategies in various building types. By incorporating EEG-based evaluations of indoor environmental quality, future building projects can prioritize occupants' well-being, leading to healthier and more engaging spaces.

In conclusion, being at the forefront of this pioneering research in New Zealand provides us with a unique opportunity to make substantial contributions to the field of IEQ and occupant well-being. Our study's innovative use of brain mapping technology opens new possibilities for understanding the connections between indoor environments and mental states, with significant implications for building design, user experience, and the creation of healthier indoor spaces. By embracing this novel approach and its practical implementations, we can drive positive change in the design and operation of buildings, ultimately benefiting the well-being and performance of their occupants.

1.6 Contribution to Knowledge

- *Revisiting the Terrain: A Neurological Frontier*

The fundamental of this research is nestled in its pioneering exploration of building functionality from the lens of user-measured experiences, through the prism of brain mapping technology – an arena that remains relatively nascent in scholarly inquiry. The study's precise focal point is the influence of indoor environmental quality (IEQ), particularly indoor air quality (IAQ) and indoor thermal comfort (ITC), on users' performance. This novel departure, evaluating functional edifices based on brain mapping (EEG) data, seeks to enrich the existing knowledge repository and proffer avenues for refining thermal performance within educational buildings.

- *Pathways to Progress in New Zealand*

This venture's novelty is underscored by its status as a vanguard in New Zealand, where its incursion into the realm of indoor environmental quality (IEQ) and its mental reverberations carries profound implications. The innovative harnessing of brain mapping technology, specifically Electroencephalography (EEG), to gauge users' experiences, carves a pioneering trail in assessing building functionality via objective neurological data. This innovative trajectory navigates beyond conventional self-reporting and surveys, unveiling more precise and credible insights into occupants' cognitive and emotional reactions to their surroundings.

- *Tangible Impacts on Multiple Fronts*

The ramifications of this research are manifold. It entails a deeper comprehension of how indoor environmental factors intertwine with occupants' well-being, cognitive prowess, and productivity. This comprehension holds pivotal implications for architects, engineers, and designers, enabling the crafting of human-centric, engrossing indoor spaces.

- *Direct and Tangible Transformation*

The tangible outcomes of our findings can catalyse direct advantages for end-users, such as students and educators in educational buildings. By tailoring thermal performance to users' experiential inputs, the study can augment learning and work environments, fostering superior concentration, engagement, and overall contentment. Moreover, the research paves the path for evidence-driven design strategies across diverse building typologies. The integration of EEG-based evaluations of indoor environmental quality augments the cognizance of occupants' well-being, nurturing healthier and more immersive spaces.

- *Filling the Gap: Reimagining Building Assessment Indices*

Amidst the evolving discourse of building assessments, a critical gap emerges: the lack of comprehensive indices that holistically encapsulate indoor thermal comfort's intricate interplay with occupant well-being and performance. Conventional indices, while robust in their evaluation of energy efficiency and environmental sustainability, often disregard the psychological nuances of indoor thermal experiences. This gap reflects a need for a paradigm shift in building assessment frameworks, one that reflects a nuanced understanding of human responses to their indoor environments.

- *A Call for Holistic Indices*

The present study advocates for the integration of indoor thermal comfort within building assessment indices. By incorporating occupants' psychological states and performance measures, these indices can redefine the assessment landscape, offering a more complete perspective of indoor environment quality.

This transformative approach ensures that the occupants' well-being and cognitive efficacy are intrinsic to the evaluation process, fostering a seamless convergence between energy efficiency and human-centric design.

1.7 Organization of the Thesis

The subsequent chapters of this thesis unfold in a structured progression, aligning with the research objectives.

Chapter 2 delves into an exhaustive literature review, drawing from diverse disciplines to underpin the theoretical foundations.

Chapter 3 extends this exploration by probing the theoretical underpinnings of indoor thermal comfort, establishing a holistic framework for subsequent analyses.

Chapter 4 traverses the realm of research methodologies, delineating the meticulous steps employed in gathering occupants' quantitative data and insights.

Chapter 5, the culmination of data analysis and findings come to the fore, shedding light on the intricate interplay between indoor thermal comfort, occupant psychological states, and measured performance.

Chapter 6 synthesizes the study's outcomes, amplifying their significance in the broader context and paving the way for actionable recommendations and future research trajectories.

Chapter 2 – Literature review: A critical review on the impact of built environment on users' measured brain activity

2.1 Prelude

This chapter presents a comprehensive review of the existing literature related to the overall impact of the build environment on the occupant brain. It serves as the foundation for the current study, aiming to critically examine and the body of knowledge in the field. The literature review provides a contextual understanding of the subject matter, identifies research gaps, and establishes the theoretical framework that underpins the present investigation.

To ensure a comprehensive examination of the literature, a systematic approach was adopted in searching and selecting relevant sources. A combination of electronic databases, academic journals, conference proceedings, and reputable books was utilized to gather a wide range of scholarly contributions. The selected sources represent a diverse array of perspectives and approaches, providing a holistic view of the research area.

This paper aims to review and analyse the research efforts that investigate the impact of the built environment on the user's state of mind, with a focus on the measured brain activities to indicate the momentary state of mind. The reviewed literature establishes that while in a natural environment the brain activities are more disentangled and meditative. Whilst in a built environment, the human brain has shown higher levels of stress. However, the mechanism in which the built environment impacts the brain is not yet thoroughly investigated. In this paper we have identified the current gaps to help shape the future towards a restorative built environment with knowledge about the human mind to maximise user benefits and well-being.

Overall, this literature review chapter is designed to provide a comprehensive understanding of the research topic, offer insights into the existing literature, and justify the need for the current study. By critically analysing and synthesizing previous research, it aims to contribute to the advancement of knowledge and serve as a solid foundation for the subsequent chapters of this doctoral dissertation.

2.2 Introduction

Due to the increasing urban growth, by 2050 more than two billion people will be accommodated in new buildings added to the current urban landscape. By 2030, the urban developed land is expected to increase by more than one million Km^2 (Goldhagen, 2017; Seto et al., 2011). This ever-growing need for building human habitats has impacted the environment, either by the land utilization for buildings or material exploration, and/or emissions (Häfliger et al., 2017). Recently, the built environment industry is aiming to reduce its footprint on the environment. Using smart technologies and building management systems, the built environment became more efficient and can save up to 20-40% of energy consumed in the building which leads to less impact on the environment (D'Oca, Hong, and Langevin, 2018; Dounis and Caraiscos, 2009).

The increasing scientific interest in greener buildings, as shown in Figure 2.1, has led to establishing a growing number of green building ratings, such as LEED, BREEAM and Green Star NZ (Doan et al., 2017; M. Shan and Hwang, 2018). Likewise, there has been growing scientific research interest in recent years towards physical well-being and the concept of a healthy built environment (Bluyssen, 2010; Ellard, 2015; Ghaffarianhoseini et al., 2018; Sarkar and Webster, 2017). These Green Buildings ratings may have contributed to guide the scientific interest towards achieving a healthier built environment and considering similar ratings for wellbeing. For instance, using biophilic approaches could shift the green building practice towards human health and wellbeing (Illankoon, Tam, Le, and Shen, 2017; Xue, Lau, Gou, Song, and Jiang, 2019). However, the impact of the built environment on our psychological well-being is not sufficiently investigated. As shown in Figure 2.1, there is a significant gap between the increasing scientific interest in green building ratings and the impact of the built environment on the human brain, even though they both are following similar trend.

Since the 19th century, scientists have sought to understand the formidable complexities of the highly-interconnected system that underpins human thought, emotion and behaviour (Abdullah, Khan, Basuhail, and Hussain, 2015; Alarcão and Fonseca, 2019; Bullmore and Sporns, 2009). The human brain is comprised of billions of interconnected cells known as neurons. These fundamental processing elements exchange information biochemically and via electrical pulses that create a spatiotemporal trajectory of sequential activities (Telesford, Simpson, Burdette, Hayasaka, and Laurienti, 2011) that culminates in human psychological reactions under different situations. The neural receptors, which functionally and practically covers all the scenes, are connected to the central nervous system -the brain and spinal cord- which control the human life (Gottfried, 2011; Papale, Chiesi, Rampinini, Pietrini, and Ricciardi, 2016). The central nervous system collects information from the entire body and coordinates activity across the whole organism to govern all forms of activities from the heart beat and involuntary reflexes, to deep thoughts and creative ideas, hence it forms our perceptual memory which encompass our mental wellbeing (Bermudez-Rattoni, 2007; Coltheart, 2002; Kandel and Mack, 2013; Milner and Rugg, 2013).

Even though the contemporary scientific definition of psychological well-being is broad and considers different aspects in Hedonic and Eudaimonic, and even physical features (Ryan and Deci, 2001; Ryff et al., 2004; Sheldon et al., 2018), this research is focused on the momentary experience of the built environment as it manifests in the human neural system; more precisely the brain. This impact of the built environment on the brain functions can be measured and analysed by suitable brain mapping technology (Kluetsch et al., 2014; Urry et al., 2004). Although it is a temporary insight, it will reflect on the user's long term psychological well-being (Poppy L. A. Schoenberg, Andrea Ruf, John Churchill, Daniel P. Brown, and Judson A. Brewer, 2018), as positive brain activity signifies physical and mental health (Bonnes and Secchiaroli, 1995; Diener and Chan, 2011). The result of the brain mapping recordings could indicate the user's state of mind, which is a measurement of his/her mood and can indicate the level of Engagement, Interest, Disengagement, Creative Inspiration, Attention, Cognition, Focus, etc. (Gegenfurtner, Kok, Van Geel, de Bruin, and Sorger, 2017; Misulis, 2013; Nidal and Malik, 2014; P. L. A. Schoenberg, A. Ruf, J. Churchill, D. P. Brown, and J. A. Brewer, 2018).

In the literature, few studies used scientific instrument measurements such as brain scanning, instead of the more common psychological analysis to investigate the impact of the built environment on the mental health. This lack of adequate research is incongruous to the impact of the subject, since the average time spent inside the built environment is 90% of the average lifespan (Evans and McCoy, 1998; Hillier and Hanson, 1989). This portion of our life span forms an essential relationship between our inner self and the surroundings that justify our behaviour (Ellard, 2015; Proulx et al., 2016).

This paper aims to review all the related research efforts that investigate the impact of built environments on the human state of mind. It predominantly focuses on the impacts on users' brain activities and their neural systems. To better understand the interrelationship between the human brain and the built environment, in context of this paper, the following terminologies should be identified:

The Built Environment	All levels (urban, building, interior, etc.) of the manmade structures that we interact with using our senses (i.e. sight, hearing, smell, taste and touch)(M. Arbib, 2015b).
Stimulus	Any element (colour, sound, design, etc.) of the built environment that evokes or sparks a corresponding nerve or neuron receptor in the human body (Bear, Connors, and Paradiso, 2016).
Momentary Experience	The transitory integration of all the stimuli which is processed by the human brain to form a temporary state of mind (Minsky, 2007).
State of Mind	The mood or mental state at a certain time which justifies the human momentary behaviour and feelings, e.g., Engagement, Disappointment, Unwind, Cognition, Focus, etc. Recently, these indications can be measured using brain mapping technologies (P. L. A. Schoenberg et al., 2018; Varela, Thompson, Rosch, and Kabat-Zinn, 2017)
Functional Brain Mapping	Advanced techniques dependent on sophisticated instruments to scan the brain waves (actual neuron sparks) with high time resolution, faster response, and the ability to plot the brain activities in real time to indicate the state of mind (Bear et al., 2016), such as Functional Magnetic Resonance Imaging MRI (fMRI) and Electro-Encephalography (EEG).
Electro-Encephalography (EEG)	EEG is considered the most common instrument for functional mapping and real-time brain wave scanning. It records and amplifies the brain's electrical signals over time to identify the corresponding indication of the subject's state of mind, by the measurement of five main waves (Cruz-Garza et al., 2017; Radüntz, 2018).

2.3 Method

This study conducts a comprehensive literature review of the relationship between the built environment and the human state of mind. It aims to identify the impact of the built environment on the human brain and critically analyse the available literature to guide the future research for healthier built environment that enhance the user experience.

In this regard, using systematic literature review following preferred reporting items for systematic reviews (Moher, Liberati, Tetzlaff, and Altman, 2009), a comprehensive literature search based on 'title/abstract/keyword' was conducted. The keywords used in the literature search were generally wide ranging and included terms related to "built environment, buildings, urban, architecture, mental health, wellbeing, EEG, neuroscience, brain mapping" in the available academic journal databases.

The databases included: Google Scholar; ScienceDirect; Scopus and Springer. Moreover, exploring the list of references of the already found articles, few papers not covered in the above databases, yet considerably important for the review were identified. Using various search engines to explore the literature assured that the weakness of one source can be covered by the strength of another. In addition, a grey literature search was conducted through Google's general search engine, using similar search terms with the aim of identifying relevant unpublished materials, government reports, and policy statements related to the subject.

During this review, over 150 articles were originally identified and classified whilst through employing content analyses, all resources were critically analysed. Only 87 papers were related to the main subject with only 52 original research study papers relating to the built environment, most of which were psychological studies. This trend was also reflected in the publication as in Table 2.1.

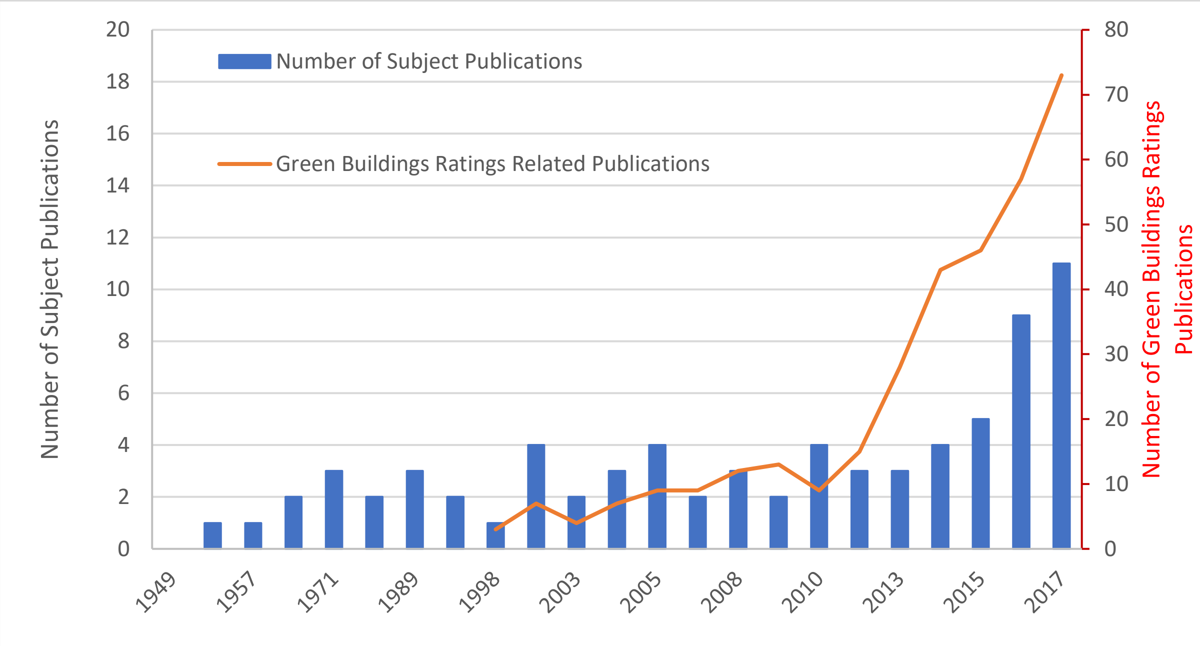
*1 **Table 2.1:** Number of related publications, based on original study, in each academic journal.*

Journal		Number of related papers	Total
Built environment related	Building and Environment	4	
	Landscape and Urban Planning	3	
	Intelligent Buildings International	3	
	Urban Forestry and Urban Greening	2	16
	Architectural Science Review	2	
	Frontiers of Architectural Research	2	
Medical / Psychology related	Journal of Environmental Psychology	7	
	Cell (and related sub-journals)	5	
	Frontiers in Psychology	4	
	Environment and Behaviour	3	
	Procedia - Social and Behavioural Sciences	3	36
	Frontiers in Human Neuroscience	2	
	International Journal of Parallel, Emergent and Distributed Systems	2	
	Journal of Cognitive Neuroscience	2	
	Journal of Transport and Health	2	
	Investigative Ophthalmology and Visual Science	2	
	Brain and Language	1	
	Journal of Cognitive Neuroscience	1	
	British Journal of Sports Medicine	1	
	Health Place	1	

The acquired information concerned with various aspects of the built environment that impact the human brain, were initially recorded in a spreadsheet, separated into columns corresponding to 'Design Elements', 'Built environment scale', 'Research methodologies and technologies', and 'Key Outputs'. The adoption of this research approach enabled the authors to systematically explore the existing body of literature, retrieve the relevant information and highlight the gap of knowledge. During the content analysis, notwithstanding the extensiveness of the collected data and synthetic process of analysing their embedded information related to the objectives of study, few limitations can be highlighted: 1)

Published in recognised scientific journals or conference proceedings in the related field, 2) Investigating, in partial or entirety, the built environment, 3) Have a generic scope, i.e. not only considering a specific category such as age or gender or mental illness, as was noticed in many excluded research, 4) The collected data and the content analysis were limited to the early mentioned utilized search engines, databases, and applied research terms.

In this research, it was found that 69% of the publications were in non-engineering or non-built environment related journals. This is considered a significant research shortage since the interference and input of medical professionals on the development process of the built environment is minimal. However, there is a noticed increase in the scientific interest as projected in the publication timeline, as shown in Figure 2.1.



*2 **Figure 2.1:** Subject related publication against green buildings ratings related publications.*

Although the psychological and social research efforts were acknowledged, the focus of this paper is to identify the measured impact of the built environment on the neural system (the brain) which indicates the state of mind. Hence all the studies depending on scientific instrument measurements, i.e., brain mapping, were mentioned in detail and critically analysed to guide future research.

2.4 Neuro-Architecture

Due to the increasing scientific interest to investigate connections between the built environment and the human neural system, the term "neuro-architecture" ascended to describe the related research efforts.

2.4.1 Definition

Neuro-architecture unites architecture and neuroscience to better understand the relationship between the human brain and the surrounding built environment. This linking is possible through different scientific techniques such as the observation of responses, physiological measures, psychological analysis and more importantly; functional mapping of different regions of the brain (J.P. Eberhard, 2009; Goldhagen, 2017). Embracing this interdisciplinary study will help to propel us into the future of architecture and design, where human health and happiness are placed at the fore. With this ever-expanding understanding of how and why humans react to environmental stimuli in built spaces, findings in neuro-architecture will increasingly inform design strategies and decisions.

According to Dougherty and Arbib (2013) "*Neuro-architectural studies architecture in terms of the effect of the built environment on the human brain: What is it about a designed space that affects the human brain and how might understanding the response of the brain lead us to improvements in architecture in the future*".

In another definition, neuro-architecture analyses the relationship between sensory experience within the built environment, as an input, and our perception of architectural spaces as an output (Papale et al., 2016). The momentary experience, as defined earlier in section 1, can be accurately indicated by brain mapping. After analysis, it can indicate the state of mind of the user which is a measurement of the user mood and can specify the level of engagement, attention, cognition, focus, etc. This measurement of the impact on the human state of mind, even being temporary, will indicate how the built environment performing its function and will reflect on the long term of the psychological well-being of users (Poppy L. A. Schoenberg et al., 2018).

In general, the main objective of neuro-architecture is to study the impact of the built environment on the neural system; which is the manifestation of human perception and an indicator of psychological well-being (Bluyssen, 2010; Pykett, 2015). These clear attempts have been developing throughout history, using the available research tools, of their time, to understand how the brain perceives its surroundings (Ellard, 2015; Jelić, Tieri, De Matteis, Babiloni, and Vecchiato, 2016). Only in recent decades the advances in medical instruments, particularly radiology and brain mapping, allowed researchers to study the impact on the neural system (Nanda, Pati, Ghamari, and Bajema, 2013; Papale et al., 2016).

2.4.2 Background

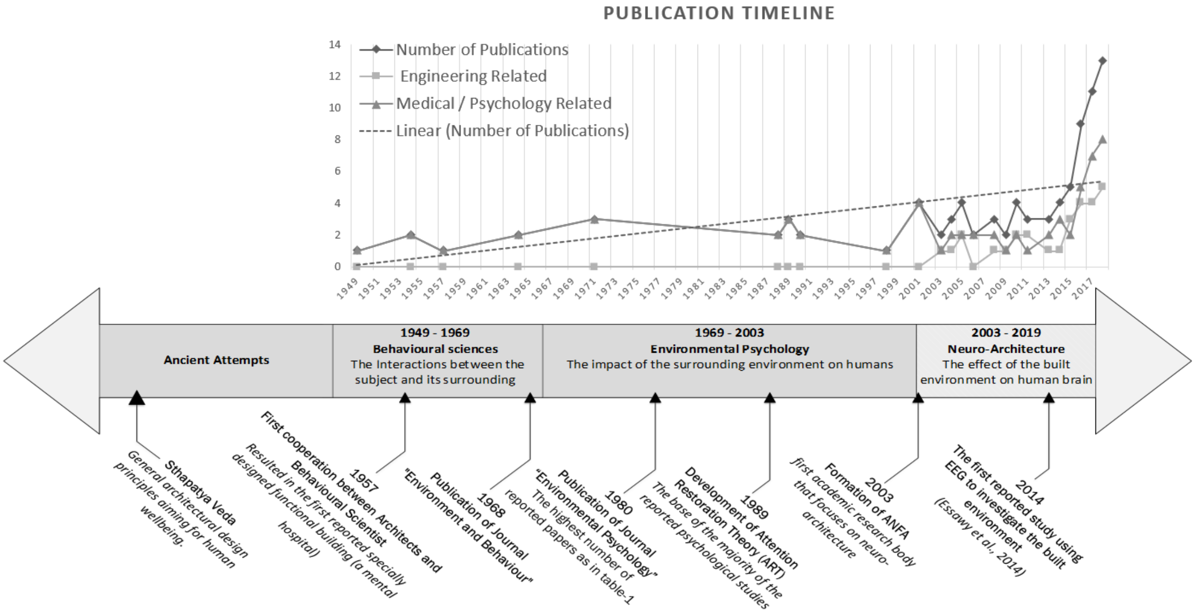
Historically, and long before the forming of neuro-architecture, there have been ancient attempts to relate the built environment to health, such as "Sthapatya Veda" or "Maharishi Vedic architecture" (Bonshek, 2001; Jakupi, 2016). These are general architectural design principles depending mainly on the orientation and layout of the house; aiming for human health and better connection between the inhabitant and habitat (Fergusson, Wells, and Kettle, 2017; Travis et al., 2005).

The early scientific studies, as viewed in the literature, are mainly related to environmental psychology. In the late 50s architects and behavioural scientists started to work together to design buildings with a specific purpose such as Osmond (1957); where he presented the cooperation between psychiatrists and architects for a specially designed functional building (a psychiatric hospital).

One of the pioneers to focus their research on the relationship between human psychology and the surrounding built environment was Roger G. Barker, particularly on the impact of school environments on children's psychological health. He was also the first to investigate the environment and behaviour differences between two different cities (Barker and Gump, 1964; Barker and Wright, 1954).

Since the 60s there has been a growing interest from researchers, mostly from a social and psychological background, which has led to the publication of two journals: "Environment and Behaviour" in 1969 and "Environmental Psychology" in 1980. Following that was the formation of the first professional research association; The International Association of People-Environment Studies, which was established in 1981 (P. A. Bell, 2001).

The term “Neuroscience” was first mentioned regarding building design in an interview from the 2003 fall issue of Society for Neuroscience, where Eberhard and Gage explained why architects and neuroscientists are beginning to work together. The same issue included the announcement of the formation of the first academic research body that focuses on neuro-architecture (the Academy of Neuroscience for Architecture (ANFA)) (Arellano, 2015; John P. Eberhard and Gage, 2003). ANFA was formed in San Diego in 2003 and is considered the first research institute to sponsor and develop the utilization of neuroscience research to better understand the human interaction with the built environment (ANFA, 2003).



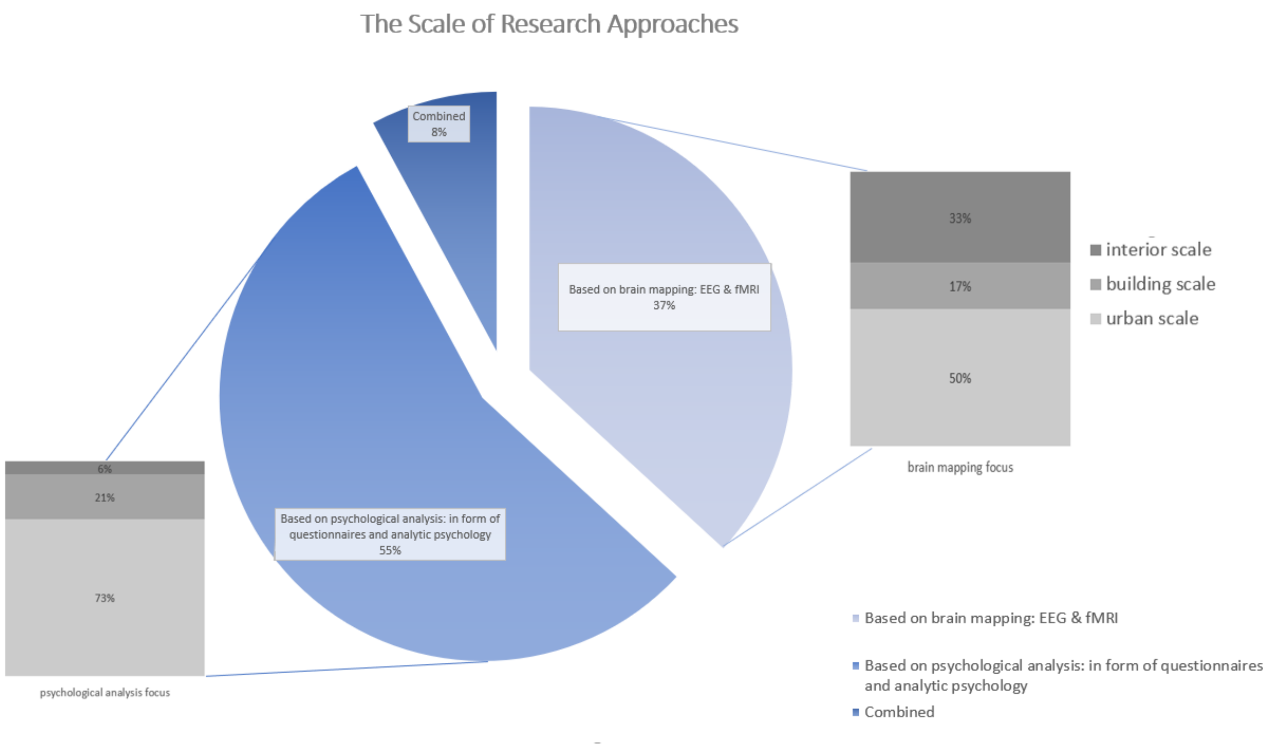
3 Figure 2.2: Subject timeline.

Showing the development of scientific interest from Behavioural Science to Neuro-Architecture along with related publication timeline.

This evolution of research interests, as shown in Figure 2.2, has led to various studies with different research methodologies to investigate the impact of the surrounding environment on the human brain. In general, the research approaches can be categorised in two main types of studies: Psychological Analysis and Brain Mapping.

2.5 Research approaches

The study of the human brain has been developing from ancient philosophical ideas to sophisticated and complex medical instruments. Similarly, the research studies found in the literature have developed from psychological analyses to technological analyses, depending on instrumental measurements. Most of the reviewed studies investigated the impact of the surrounding environment on the human experience. The higher percentage are using social and psychological analyses, as shown in Figure 2.3.



*4 **Figure 2.3:** The scales of the different research approaches demonstrated in the literature.*

These number are only for experiment or scientific measurement-based research. The percentage is based on a total of 52 reported studies.

Arguably both have advantages, psychological analysis studies are more indicative for long-term psychological well-being, whereas brain mapping depends on accurate and advanced scientific measurement but is more momentary in nature (Emmons and King, 1988; Urry et al., 2004). Therefore, to isolate the impact of only the built environment on the long-term psychological well-being, the momentary measurement is considered more indicative (M. Arbib, 2015a).

Due to the technological limitation, the brain mapping studies have a much lower scale compared to the psychological studies. Only in recent decades, the emergence of scientific technologies has allowed researchers to accurately detect the brain activity that indicates different states of mind (M. Arbib, 2012; Nanda et al., 2013). On the other hand, the reviewed psychological analysis studies are not strongly dependent on technology and scientific instruments.

2.5.1 Psychological approach

Psychological studies can be based on self-reported questionnaires, an investigative interview conducted by a specialist, or such other analytical techniques, to report the subject's state of mind. They are mainly designed to measure the mood or mental state of the subject, e.g. Brunel Mood Scale also known as BRUMS, Profile of Moods States (POMS), Positive and Negative Affect Schedule (PANAS) which is a self-reported scale-based questionnaire, and Backward Digit Span (BDS) which is a measure of working memory used to assess the brain functions (Berman, Jonides, and Kaplan, 2008; McNair and Heuchert, 2007; Watson, Clark, and Tellegen, 1988).

Most of the studies are related to the Attention Restoration Theory (ART) which proved, and explained, that exposure to nature leads to positive effects on psychological health. According to ART, most natural scenes capture the attention in an enjoyable and straightforward manner, letting the brain to rest and wander freely (Kaplan and Kaplan, 1989).

2.5.2 Psychological studies in the literature

In their work, Van den Berg, Joye, and Koole (2016) have investigated the difference between viewing nature and the built environment. They used different scaled photos that showed different levels of complicity in both nature and the built environment. By measuring the time of viewing and the subject feedback, they concluded that the participants had positive responses to natural scenes and to the fractal patterns that are more commonly found in nature (Mandelbrot, 1982). This suggests that fractal complexity may be a key factor that makes natural scenes more attractive and uplifting than manmade building scenes. Therefore, fractal dimension for natural landscape preference can produce designing guidance to imitate nature in the built environment (Hagerhall, Purcell, and Taylor, 2004). Depending on the same theory of ART, Valtchanov and Ellard (2015) conducted a similar study, using images with different resolution. Their research confirmed that viewing urban scenes increased blink rates and cognitive load compared to displaying scrambled, low-resolution images and natural images.

Ulrika Karlsson Stigsdotter, Corazon, Sidenius, Refshauge, and Grahn (2017), aimed to identify which qualities and perceived sensory dimensions (PSD) of the natural environment have a healing psychological impact. The result showed that PSDs of peaceful, diverse, natural surroundings have the highest psychologically healing results. This study shows the potential for using the PSDs as guiding principles for designing healthier built environments (Grahn and Stigsdotter, 2010).

Few studies have used physiological measurement along with psychological measurement for validation. U. K. Stigsdotter, Corazon, Sidenius, Kristiansen, and Grahn (2017) measured systolic and diastolic blood pressure and Heart Rate Variability (HRV) as an indicator for the body's state of tension or relaxation. Similar to this study, Gidlow et al. (2016) used HRV measurements but adding salivary cortisol and Rate of Perceived Exertion (RPE) measurements. Their results proved that walking in a natural environment leads to greater restorative experience and better cognitive function.

There are other, early mentioned, research efforts that have used psychological approaches to identify the impact of the Indoor Environment Quality (IEQ) on the humane experience, such as: Mendell and Heath (2005); Tham and Willem (2010); Tsutsumi, Tanabe, Harigaya, Iguchi, and Nakamura (2007); Wargocki, Wyon, Sundell, Clausen, and Fanger (2000). These efforts, even though they show a direct relationship between IEQ and the user's performance, have not established the direct impact on the user's mental state which manifests as performance (P. L. A. Schoenberg et al., 2018).

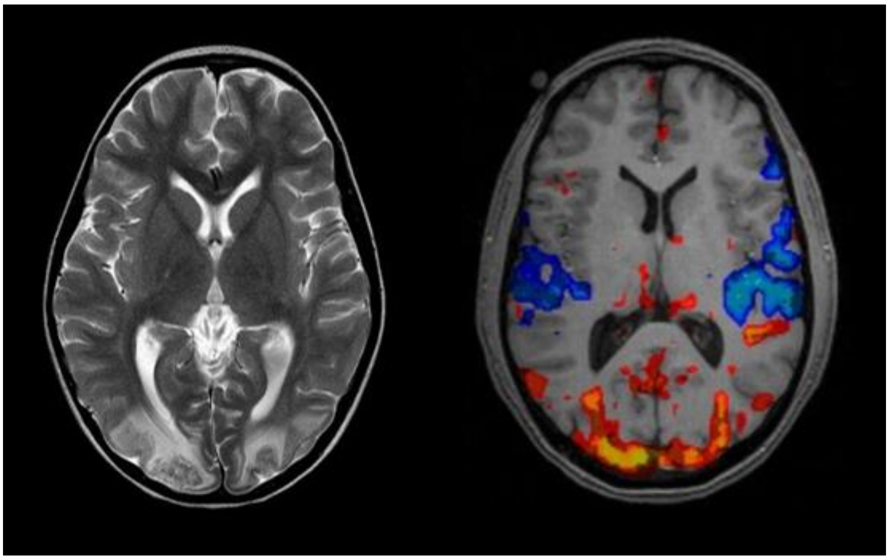
The literature includes more studies, that can be described as social or psychological, on how the built environment and nature impact the psychological well-being (Amirbeiki Tafti, Rezaeian, and Emadian Razavi, 2018; Essawy, Kamel, and Elsawy, 2014; Hartig, Mitchell, de Vries, and Frumkin, 2014; Hinckson et al., 2017; Kjellgren and Buhrkall, 2010; Koohsari, Karakiewicz, and Kaczynski, 2012; Korpela, De Bloom, Sianoja, Pasanen, and Kinnunen, 2017; Korpela, Nummi, et al., 2017; Steemers and Manchanda, 2010; Stewart et al., 2016; Swami, Barron, and Furnham, 2018; Tilley, Neale, Patuano, and Cinderby, 2017). However, only those studies that have key outcomes towards designing the future built environment, i.e., using fractal patterns or PSD, were discussed in this section.

Most of the reviewed research's methodologies had a comparative approach; the researchers were more contingent on comparing the impact of nature and the impact of the built environment. This methodology has established and proofed the deviation, between the built environment and nature, but didn't explain the mechanism or identified the critical factors of the built environment that augment the state of mind. The recent technological progress, particularly in brain mapping, has a vital role to fill these gaps.

2.5.3 Neuroscience and brain mapping approaches

Over the last few decades, a marked increase in interest in understanding neuropsychological mechanisms of human behaviour has spurred an eruption of innovative methods to measure and interpret brain activities. This approach is considered more technologically advanced as it depends on sophisticated instruments to scan the human brain. According to Duffau (2011); J.P. Eberhard (2009); Gegenfurtner et al. (2017), there are different methods to map the brain structure and activity, and each has a favourable purpose:

- Structural Imaging which provides representation of the brain structure by:
    a. Computerized Tomography (CT): It computes several X-rays from different angles to plot a two-dimensional horizontal section of the brain (Bear et al., 2016).
    b. Magnetic Resonance Imaging (MRI): Like the CT but instead it uses a strong magnetic field to plot at a higher resolution and more sections than CT (Duffau, 2011).
    c. Water Diffusion MRI (dMRI). This is more advanced and allows mapping of the brain wiring (Duffau, 2011).
- Functional imaging techniques which can provide functional information on various parts of the brain:
    a. Positron Emission Tomography (PET): This measures the blood flow to determine the activity of the brain tissue (Bear et al., 2016)
    b. Functional MRI (fMRI): This is more advanced and accurate, it uses the same concept as PET but measuring the local blood flow (Duffau, 2011).



5 ***Figure 2.4***: *Comparison between MRI and fMRI.*

The MRI (left side) image shows a static brain structure while fMRI (right side) shows different levels of the brain cell activities (Duffau, 2011).

More recently, there have been more advanced techniques that provide higher time resolution, faster response, and can measure the brain activity in real time (Bear et al., 2016), such as:

- Electro-Encephalography (EEG):

This measures the fluctuations in the electrical signals across the brain by using sensitive electrodes placed on the subject's scalp. The electric signals are collected instantaneously from the multiple electrode locations resulting in real-time brain activity mapping (Nidal and Malik, 2014).

- Magnetic Encephalography (MEG):
  Measures the tiny changes in the magnetic field generated by the electric current in the brain. The signals are perceived by superconducting quantum interference device (SQUID) sensors. The signals are very small (10^{-15} Tesla) so to avoid contamination, the recordings take place in a magnetically isolated room (Bear et al., 2016).
- Transcranial Magnetic Stimulation (TMS):
  This depends on electromagnetic induction by creating a magnetic field through the subject's skull which causes a tiny electric current in the subject's brain, simulating the neural tissues. TMS has been used generally in exploring visual perception yet it is considered hazardous and must be used with caution as it may cause seizures (Zillmer, Spiers, and Culbertson, 2007).

Both MEG and EEG have a high time-based resolution and instant recording but lower spatial resolution. Therefore, for accurate structure and functional mapping, it is common to combine MEG or EEG with fMRI for high temporal and spatial resolution (Bear et al., 2016).

Most of the studies in the literature used EEG for brain mapping (Banaei et al., 2017; Hollander and Foster, 2016; Shemesh et al., 2016). This could be due to the mobility of EEG and the relative lower price compared to fMRI or MEG. Among the available neuroimaging technologies EEG features excellent resolution of neural activity in the time domain, and it is considered the most reliable and predicative instrument when studying human cognition, evaluating a subject's health condition, or monitoring their mental state (David Hairston et al., 2014; Radüntz, 2018).

2.5.4 Electro-Encephalography (EEG)

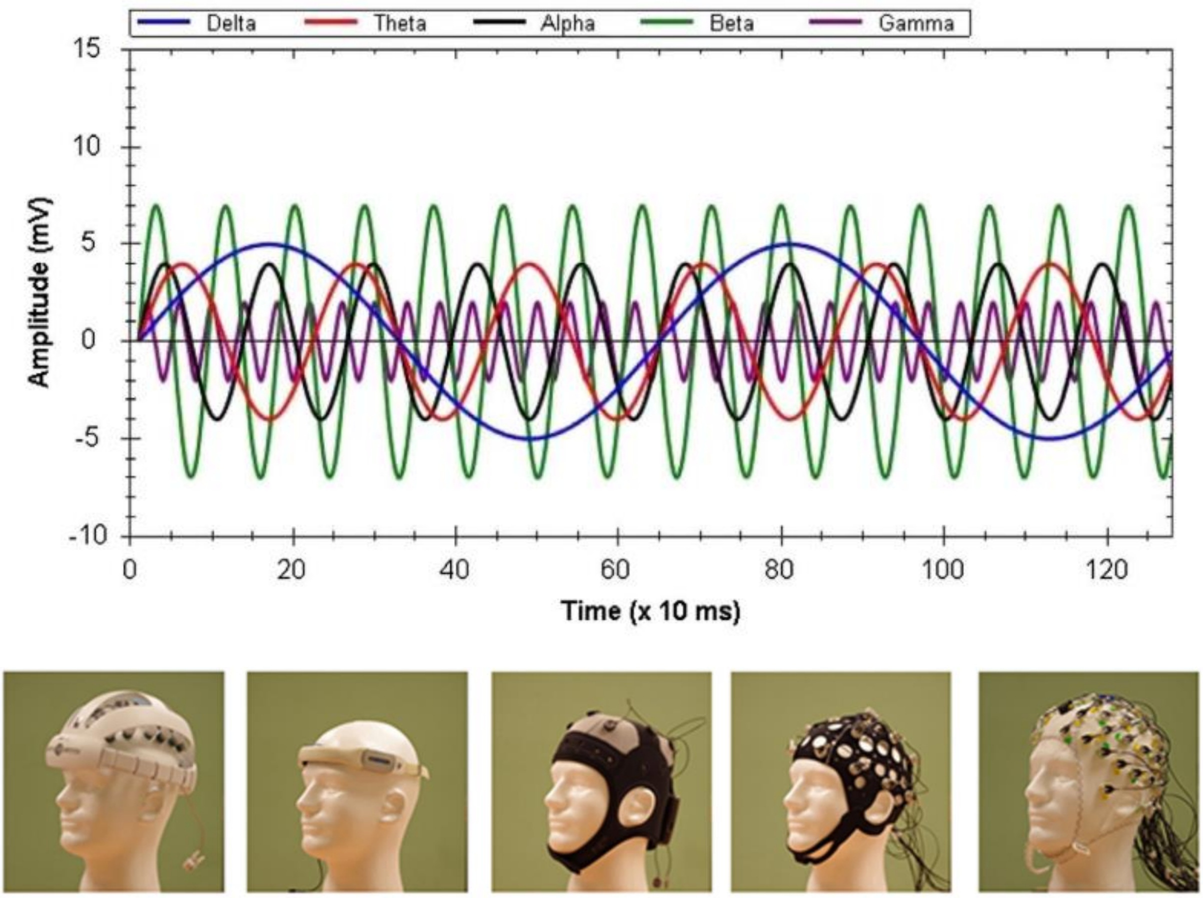
EEG provides a direct measure of electrocortical activity with millisecond precision and is sensitive to changes in arousal, perception and cognitive function (M. A. Bell and Cuevas, 2012). More specifically, EEG measures changes in extracellular potentials from large arrays of neurons, predominantly pyramidal cells. EEG signal patterns vary in different cognitive states according to the voltage fluctuations resulting from ion flow between neurons. The frequency of the voltage fluctuations is measured using EEG spectra (Freeman and Quiroga, 2012).

The EEG signal oscillation is rhythmic; thus, it is typically described in terms of bands of different frequencies as reported in Table 2.2 (Duffy, Burchfiel, and Lombroso, 1979; Gevins and Rémond, 1987; Misulis, 2013; Nidal and Malik, 2014; Nuwer et al., 1999; Quiroga and Schürmann, 1999):

*2 **Table 2.2:** Major Brainwaves detected by EEG and how it is interoperated.*

Wave	Range (Hz)	Mental state indication	Manifestation
Alpha (α)	7-13	Disengagement, relaxed, unwind, disentangled	They appear spontaneously in normal adults during wakefulness, under relaxation and mental inactivity conditions. They are best seen with eyes

				closed, most pronounced in the occipital locations.
Betta	(β)	13-30	Engagement, focused, computing	They are the best defined in central and frontal locations, with less amplitude than alpha waves. They are enhanced upon mental calculations, expectancy, or tension over the entire surface of the scalp.
Delta	(δ)	0.5–4	Sleeping, unconscious	They are characteristic of deep sleep stages. Depending on their morphology, localisation, and rhythmicity, delta oscillations can be normal as in slow wave sleep or pathological as in brain tumours.
Theta	(θ)	4–7	Lower Range: Unconscious, creative inspiration, deep meditation Upper range: Frustration, dissatisfaction	They are typical during deep sleep. They play an important role in infancy and childhood. In the awake adult, high theta activity is considered abnormal and related to brain disorders, such as epilepsy.
Gamma	(γ)	> 30	Attention, cognition, perception	Low Gamma rhythms (30-60 Hz in human EEG): of minor interest until the 1990's, gamma oscillations became very popular after they have been proposed to play a major role in linking stimulus features into a single perception. Several follow up works have shown correlations of gamma activity with different sensory and cognitive processes, notably during visual, auditory, somatic, and olfactory perception as well as with attention. High Gamma rhythms (variously defined between 80 and 120 or above) also called epsilon rhythms have been found in both human and animal Electrocorticographic (ECoG) in association with chattering action potentials.



*6 **Figure 2.5:** EEG measured waves and their relevant amplitude which represent the wavelength of each different brain wave.*

Bottom, different models of EEG scanners, with different number of electrodes (Cruz-Garza et al., 2017).

However, EEG still has several shortfalls that need further development. Firstly, Emotion Recognition techniques and software have varied accuracy; they are questionable based on the source and subjects as it is difficult to separate the cause of the change in the subject's state of mind. Nevertheless, some new methods have been developed such as Domain Adaptation Network (DAN) for knowledge transfer which showed an increase of 20% in accuracy over the traditional methods (Jin, Luo, Zheng, and Lu, 2017). Secondly, during the subjects' brain mapping many artefacts occur due to electrode movement, physical movement, optical movement and more widely reported muscle electrical activity (Islam, Rastegarnia, and Yang, 2016; Brenton W. McMenamin et al., 2010; Olbrich, Jödicke, Sander, Himmerich, and Hegerl, 2011).

2.5.5 Brain mapping studies in the literature

More recently, advanced research has been developed that utilizes neuroscience and brain mapping technology to accurately identify and measure the impact of the built environment on the human brain (Coburn et al., 2017; Mavros, Austwick, and Smith, 2016; Vecchiato et al., 2015).

Accordingly, Aspinall et al. (2015) have used EEG to compare between three different settings -green park, urban shopping area and commercial crowded space- using emotion recognition software (Emotiv). They have found that urban shopping neighbourhoods and green covered routes showed a higher level of excitement, which dropped down during a crowded commercial route. Moving from an urban area to a green area led to decreases in frustration, excitement, and engagement, whereas the meditative state increased. In contrast, moving from green area to crowded commercial areas lowered the meditation state, and increased engagement.

Shemesh et al. (2016) have combined EEG and virtual reality (VR) to measure the effect of different architectural space geometries on the human brain activity. The study indicated that brain activity occurring in the first 2 seconds of exposure to a specific space is critical as adaptation occurs within this period. It showed that in the first 2 seconds, the viewer sweeps the image and analyses it, and then only after this first 2 seconds stage viewers tend to focus on finer details.

Similarly, using the same combination of VR and EEG, Banaei et al. (2017) compared 69 different VR-rooms representing 17 different clusters of interior-design/architectural style. They outlined significant differences between the impact of linear and curved geometries on brain activity. Rooms associated with lower pleasure and arousal ratings (lower anterior cingulate cortex activity) contained more linear geometries, while rooms with higher pleasure and arousal ratings (higher anterior cingulate cortex activity) contained more curved geometries. This study is inline with and confirms the same results of Vartanian et al. (2013) where fMRI was used instead of EEG.

Another study by Banaei et al. (2015) has used EEG to investigate the human brain activity while walking on two different trails in the city. The EEG results showed that the subjects were more relaxed with lower arousal levels and less anxiety; had higher alpha activity during the first 3 minutes of the park trail, however, this state faded after 3 minutes.

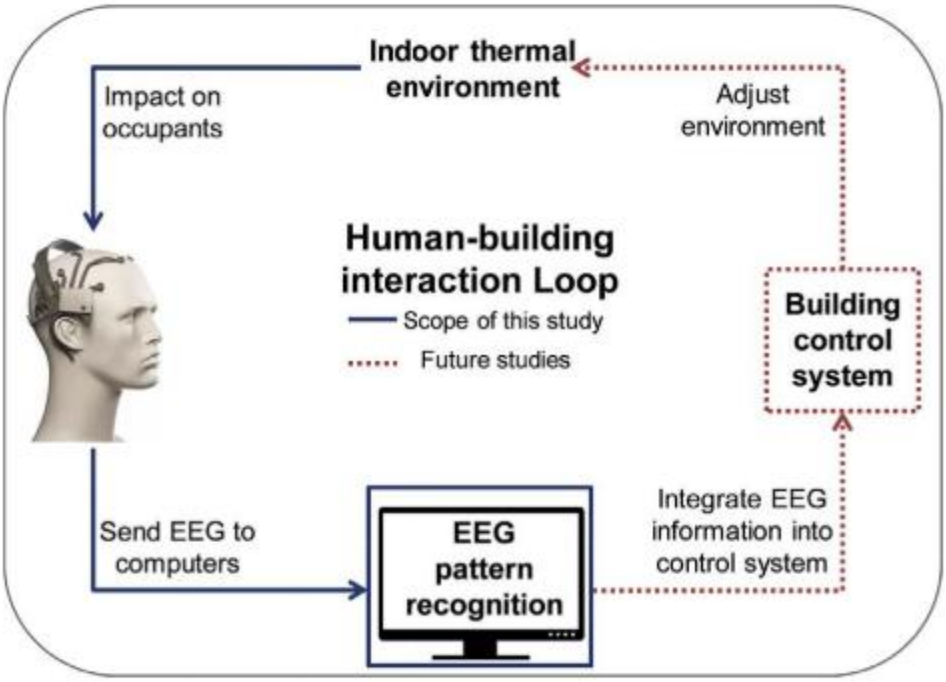
Investigating a different scale of the built environment -the urban scale- and using EEG, Karandinou and Turner (2018) studied the relationship between the change of the built environment surrounding the subject and their brain activity. While navigating through different urban routes, subject's wore portable EEG devices. They concluded that brain activity is much more engaged and complex, with higher beta activity indicating the interest of the subject, in the outdoor urban spaces in comparison to the indoors of buildings (Aspinall et al., 2015).

In a similar study, Hollander and Foster (2016) compared walking between two different neighbourhoods with 10 participants wearing portable EEG monitors. The result showed that participant's brain activity had a higher state of relaxation (Alpha waves) in residential areas than in business areas. It should be mentioned that in this study, the EEG device had only two electrodes which indicate lower resolution and accuracy.

More recently, and in the latest proceedings of ANFA (ANFA, 2018), there are several reported and ongoing studies that used EEG for different investigations of the built environment. With a focus on the change in brain waves corresponding to different architectural designs; Zakaria Djebbara has investigated the impact of moving between two spaces with different dimensions while wearing an EEG device. Turk et al., have combined the EEG scanning of the future users with a functional building (a middle school) to increase concentration, focus and cognitive brain activity within the building. Ergan et al., have tested the impact of different interior designs on the motivation to work and they concluded that stimulating environments can increase the arousal levels by 19%.

In all the reviewed literature there were few related studies (Choi, Kim, and Chun, 2015; X. Shan, Yang, Zhou, and Chang, 2018) that have attempted to link the Indoor Environment Quality to the state of mind. X. Shan et al. (2018) used EEG to enhance human building interaction under various indoor temperatures. Correlations between EEG and subjective perceptions/task performances were experimentally investigated. They tested the subject feedback (in questionnaire form) against three different temperatures: 23, 26, and 29 °C. The result was compared against the EEG readings to identify the brain wave patterns against the subject's thermal feeling (warm, cold, etc.). They have used these parameters to build a machine learning-based EEG pattern recognition mechanism, as shown in Figure

2.6, which is based on their EEG readings, of several tasks, performed by the participants, in different conditions. X. Shan et al. (2018) reported that a neutral thermal condition (26°C) led to more positive emotion than the other two thermal conditions (23 and 29 °C) which were similar. The EEG recorded waves were related to the thermal acceptability in the subjective questionnaire.



*7 **Figure 2.6**: EEG-based methods as a feedback mechanism of occupants to improve the human building interaction, adopted from X. Shan et al. (2018).*

In another study, focused on IEQ, Choi et al. (2015) have examined the effects of the indoor environment on stress levels. Temperature, odour irritants and sound were selected as environmental elements to be studied within the combined environment and were individually controlled in a total of 12 combined environments, within a climate chamber. Experimental results indicate that occupants' stress levels were maximized when they were exposed to a temperature of 30 °C, odour irritants (VOCs) and to road traffic noises.

These studies have been consistent with the results of the mentioned studies cited in Section 2.4.2 proving the variations of brain activity when changing the surrounding environment, more precisely the deviation of the impact of natural surroundings versus the built environment on the state of mind. The literature did show a decline in research relating to brain mapping methodology, especially in fMRI and other mapping methods. However, in general all the studies had consistent results and some studies have validated their results using the two earlier mentioned approaches.

2.5.6 Combination of brain mapping and Psychological studies

Two of the mentioned studies have used psychological tests along with brain mapping to validate their result (Shemesh et al., 2016; Tang et al., 2017). There was no variation in the results between the psychological and the brain mapping results.

Tang et al. (2017) used functional Magnetic Resonance Imaging (fMRI) to compare the impact of different landscapes (urban, mountain, forest, and water) on the regional brain activity. The brain mapping indicated different responses to urban and natural environments. In the visual and attentional areas in the brain, especially in the "urban versus water" landscape comparison, the right cingulate gyrus and left praecuneus were activated. These regions are known as the dorsal posterior cingulate cortex and are assumed to influence the focus of attention by adjusting whole-brain metastability (Hagmann et al., 2008).

Nevertheless, it should be mentioned that in Tang et al. (2017) there was no difference in the brain activity regions when comparing urban versus forest environments. According to this finding, the brain response upon viewing urban and forest images was similar but this was not reflected in the psychological results.

In conclusion, all reported studies have proved that the change of the surrounding environment has a direct impact on human state of mind. All reviews have demonstrated a variation of the measured brain waves (Alpha, Beta, Delta, Theta, and Gamma), or a change in the physiological or psychological features, while viewing or navigating different environments. These findings, even varied in their focus, collectively showed that the built environment directly impacts how the human brain is shaped.

2.6 Analysis of the reported studies

The research outlined in section 4, had a variety of scope and methodologies. In general, there was no contradiction between the brain mapping results in the literature; all the studies have shown a change in the different waves corresponding to engagement, excitement, relaxation, etc. when changing the surrounding environment, especially from an urban to a natural environment.

Overall, the main features of the reported studies are comparative, with no depth into the mechanism of the impact, or identifying the critical factors of the built environment that augment the state of mind, such as determining an element (colour, scale, shape, etc.), that has a direct impact on the brain. Also, there is a lack of investigating the different features of the built environment, e.g. only three reported studies (Banaei et al., 2017; Vartanian et al., 2015; Vartanian et al., 2013) compared different architectural designs to identify the main features that lead to healthier brain activity or the contrary. This represents the leading research gap which needs to be addressed to shape any guidelines or design recommendations for healthier built environment. As shown in Figure 2.7, most of the studies can be categorized into five main research focuses with no depth or detail on the design features or the mechanism of the impact.

In the reviewed literature, only few studies, summarized in Table 2.3, were based on accurate measurements and brain mapping tools. Those studies, even with the mentioned remarks on their methodologies, have shown a constant variation in the measured brain waves.

3 ***Table 2.3:*** *Summary of the research studies based on brain mapping.*

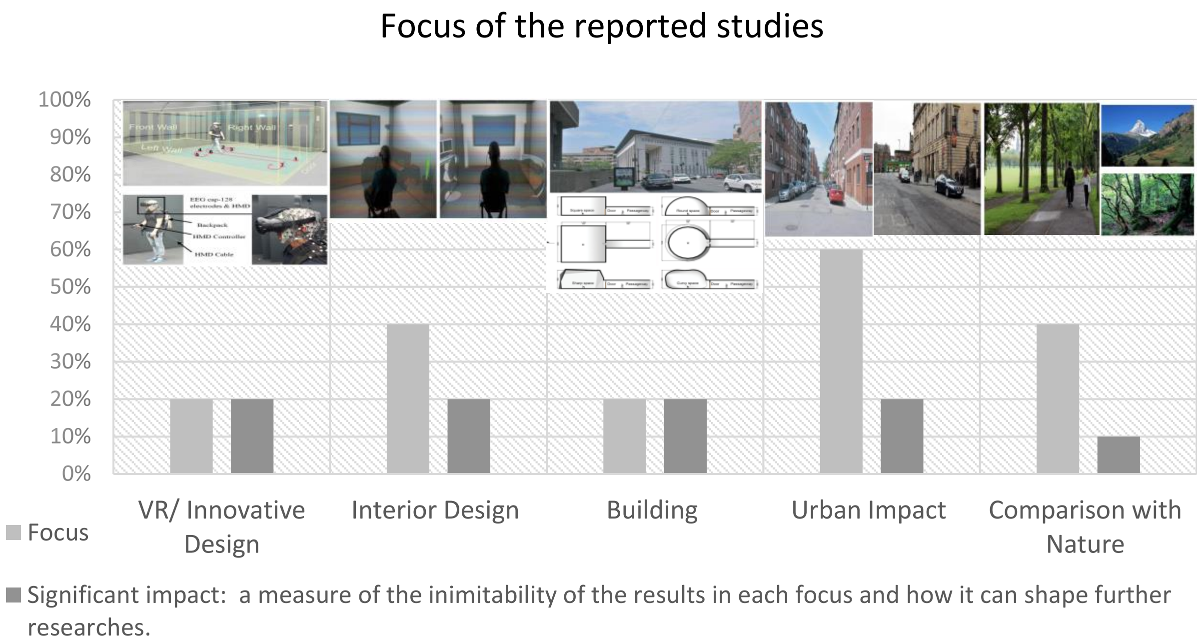
Study	Instruments	Investigation	Key findings	Remarks
(Tilley et al., 2017)	• EEG • Interviews	Compare the Urban vs. natural environment.	A positive effect of green space. Higher engagement and excitement (Betta waves) and lower levels of frustrations (upper Theta range).	Small sample, only 8 subjects were able to complete the two parts of the research.
(Shemesh et al., 2016)	• EEG • VR • Questionnaires	The effect of different architectural space geometries.	The first two seconds of exposure to space are critical to brain adaptation.	The VR spaces are empty and don’t represent the actual real built environment.
(Karandinou and Turner, 2018)	• EEG	Navigation in different urban roots.	Higher brain activity in the outdoors urban spaces. Beta waves are increased when encountering people.	The rout of the journey was not fixed which involved the subject to make navigational decisions.
(Hollander and Foster, 2016)	• EEG	Walking within two different neighbourhoods; residential vs. business.	More comfortable in the residential than in the business neighbourhood.	The EEG device had lower resolution and accuracy.
(Banaei et al., 2015)	• EEG	Walking on two different trails; Park vs. commercial.	Lower arousal levels and less anxiety during the first 3 minutes on the park trail, more excited on commercial trail but this state faded after 3 minutes.	The commercial trail was a historic attraction.
(Aspinall et al., 2015)	• EEG	Comparing green park, urban shopping areas and commercially crowded spaces.	Urban shopping areas and green routes showed a higher level of excitement. Moving from green to crowded commercial: meditation state dropped, and engagement increased.	The study is based on twelve students without background diversity.
(Banaei et al., 2017)	• EEG • VR	Comparing 69 different VR-rooms representing 17 different clusters of architectural style.	Rooms with higher pleasure and arousal (Theta waves) ratings contained more curved geometries.	The study is based only on VR experience.
(Essawy et al., 2014)	• EEG	The impact of spiritual buildings on the human brain.	Higher state of relaxation and calm awareness (Alpha waves) when staying inside the buildings.	Only a three-electrode EEG device was used.
(Tang et al., 2017)	• fMRI • Questionnaires	Comparing urban, mountain, forest, and water environments.	Different response to urban and natural environments especially water landscapes; right cingulate gyrus and left praecuneus were activated.	No difference in the brain activity regions when comparing urban versus forest environments.

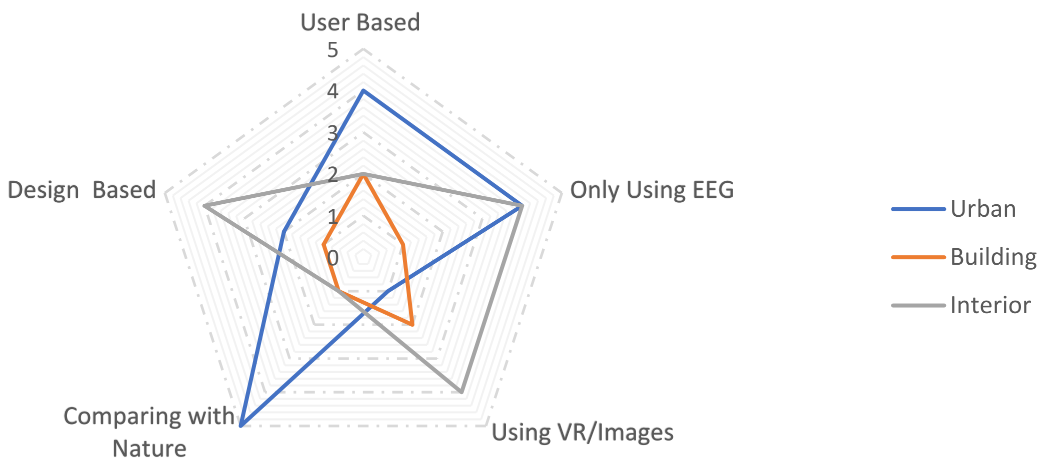
				The study was based on viewing images only*.
(Vartanian et al., 2015)	• fMRI	Ceiling height and open vs. enclosed spaces	Higher ceilings and open spaces are more attractive. Enclosed spaces more avoided by the subjects.	The study is based on viewing images*.
(Vartanian et al., 2013)	• fMRI	Comparing rectilinear and curvilinear interior spaces.	Curvilinear spaces activated the aesthetic processing part of the brain.	The study is based on viewing images*.

* All fMRI studies are based only on viewing of images not on real time full experiences. This is due to the complexity and size of the scanning machine. However, fMRI offers more structural mapping and higher spatial resolution as mentioned in section 4.2.

There are a few research efforts not reported in this section due to their focus on different aspects of the built environment such as navigation and decision making in urban areas (Erkan, 2018; Juliani, Bies, Boydston, Taylor, and Sereno, 2016; R. Li and Klippel, 2014; Vecchiato et al., 2015) These studies acknowledged that unique designs and landmarks are critical elements for spatial recognition. Similarly, there were few research interests that focused on the thermal comfort and its impact on the user's mental state (Choi et al., 2015; X. Shan et al., 2018).

The highest research focus, with 60% of the reported studies, is Urban scale. This is because few published studies have tried to compare nature trails with built environment trails, building on the previously mentioned theory "Attention Restoration Theory (ART)". This was also reflected on the significant output of the urban scale studies, as shown in Figure 2.7, which is relatively low because of the similarity of reported research in this focus.





*8 **Figure 2.7:** Scale and volume of each different subject of the built environment in the reported studies.*

Top, the focus scale of the mentioned brain mapping studies. Bottom, the volume of each different subject of the built environment in the reported studies. These graphs are based only on the reported studies in Table-2.3, Brain mapping studies. Images adopted from: (Aspinall et al., 2015; Banaei et al., 2017; Hollander and Foster, 2016; Shemesh et al., 2016; Vecchiato et al., 2015).

As highlighted in Table 2.3 and section 2.4.5, most of the studies used EEG for brain mapping. There is no literature that combined EEG with another brain mapping instrument to add more detail to the results. The declined number of approaches and research methodologies is also reflected in the focus of the reported research, as shown in Figure 2.7. The significant impact of the reported research has declined as only few studies have identified key elements that have a direct impact on the change of the human brain waves.

One general consideration, for all the reported studies, is the separation of stimuli. For example, in all fMRI studies, the fMRI scanner is noisy and it can impact the subject's state of mind (Roberts and Christopoulos, 2018). Likewise, in all the EEG studies in the outdoors, there are many other stimulants that could affect the state of mind like noise, odour, navigation, physical fatigue and walking which impact the EEG signal and requires further processing to ensure the accuracy of the signal attribution.

Similarly, the detection and removal of artefactual activity that often contaminates the EEG results is not reported in the studies. During a subject's brain mapping, many artefacts occur due to electrode movement, physical movement, optical movement and more widely reported; muscle electrical activity (Islam et al., 2016; Brenton W. McMenamin et al., 2010; Olbrich et al., 2011). Although there are several studies in the literature for effective detection and filtration of the EEG signals (Islam et al., 2016; Kumar, Sharma, and Tsunoda, 2017; S. A. Weiss et al., 2017), the reported brain mapping studies did not elaborate in detail on the isolation of muscles' electrical activity, as most of them involved physical movement or at least optical movement. Finally, raw EEG signals are normally weak with very low amplitudes and are generally contaminated by artefacts and noises. Therefore, pre-processing of these raw signals is mostly carried out to remove such contaminations (Kumar et al., 2017).

Further comprehensive approaches are required to isolate each stimulus, i.e., design elements, to accurately detect the impact of the surrounding environment on the subject's state of mind. Considering the human factor and the sensitivity needed to measure complex brain activity, highly advanced and detailed research efforts are required that might even go for decades and necessitate a global database, such as the "Human Brain Project" (Amunts et al., 2016). Further interdisciplinary research projects involving new emerging sciences and methods is required to identify the impact of each element of the built environment on the human brain, e.g. using machine learning methods to classify the emotional state of EEG readings (X.-W. Wang, Nie, and Lu, 2014).

2.7 Discussion and conclusion

The human brain has more invigorating brain activity, indicated by EEG, when in the natural environment (J. W. Zhang, Howell, and Iyer, 2014). There are even some theories that claim an evolutionary root of attraction to the aesthetic nature and how it enhanced our chances of survival (Dutton, 2009; Etcoff, 2011). Moreover, current urban planning practices already uses nature settings and parks for their impact on the brain (Qin, Zhou, Sun, Leng, and Lian, 2013).

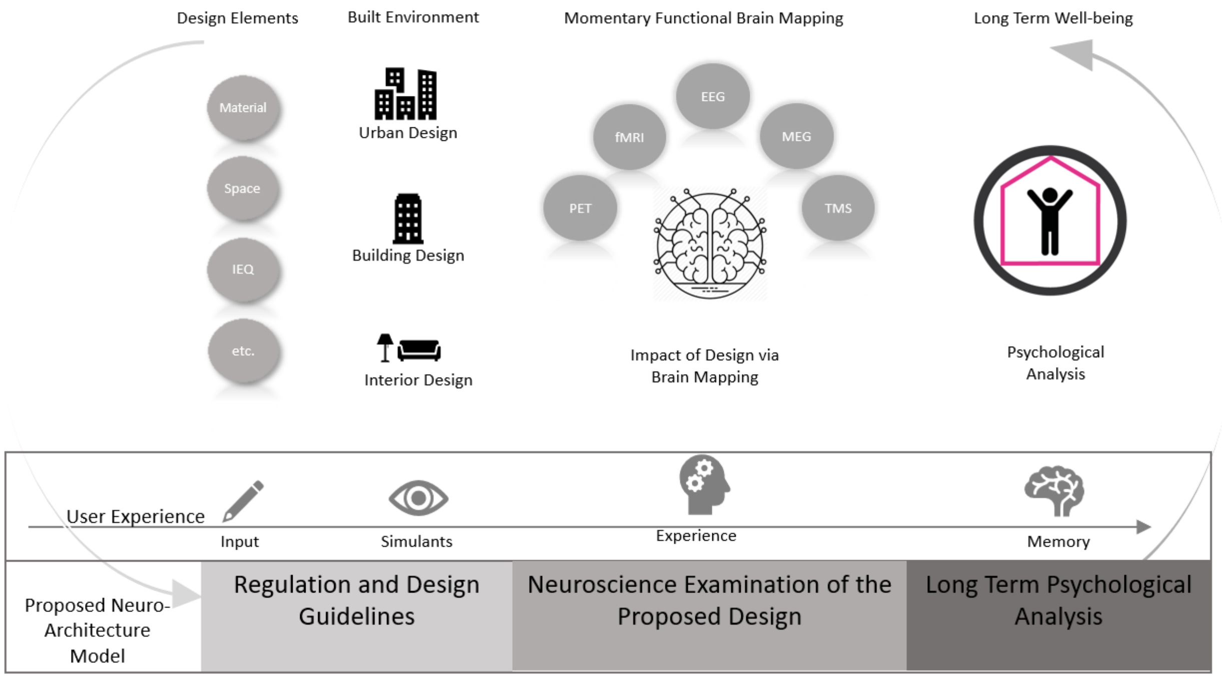
Winston Churchill said " *We Shape our buildings; Thereafter they shape us*" (Brand, 1995). However, during the architectural design process, there is negligible consideration to the impact of the built environment on psychological well-being and mental health (Goldhagen, 2017). Although in the current engineering codes and green rating/certification guidelines such as, LEED (LEED, 2017), BREEAM (Global, 2016) or Green Star NZ (Doan et al., 2017), there are many regulations regarding indoor air quality, natural light exposure, etc., that promote a healthy environment, there is no regulation or guideline towards mental health or the impact of the built environment on the brain. In current urban planning practices, mental health has been neglected even through smart design solutions to avoid traffic or to ensure high quality of urban settings that would positively impact our psychological well-being (Bornioli, Parkhurst, and Morgan, 2018; Kjellgren and Buhrkall, 2010).

The only related guidelines that mention the impact on the neural system were found in WELL building standards (IWBI, 2017a):

"The WELL Building Standard places the utmost importance on supporting neurologic and cognitive function through a variety of interventions. Features work to limit the exposure to environmental toxins in air and water, encourage balanced diets and optimal levels of physical activity, and enhance sleep quality and mitigate stress through the implementation of a variety of comfort measures."

Most of the mentioned measures are like LEED, BREAM and Green star NZ. The only additions are the promotion of eccentric and mindful designs, without any specific design elements and features, and the requirement for a mental health care facility within a 1.6 km (1 mile) walking distance of the community boundary (IWBI, 2017b).

This lack of specific regulations or guidelines is critical and needs to be addressed, as mentioned before the average time spent in the built environment is 90% of the lifespan. This portion of our lifespan is critical in forming our perception and it magnifies the relationship between the built environment and our psychological well-being. The future research must investigate the different levels of human interaction with the built environment to better understand the impact on the human brain, see Figure-2.8.



*9 **Figure 2.8:** proposed framework to include the user's wellbeing in the design process.*

The different scales of required research to understand the impact of the built environment on the human perception, with proposed procedures to include the user's wellbeing in the design process.

The central research gap is that the reported studies have limited significant outputs. They mostly focused on proving the impact of the built environment but have no detailed research with a precise focus on a single design element to investigate the mechanism or to identify a specific feature of the built environment. Even though several studies have reported a deviation between the built environment and natural restorative surroundings, the cause of such deviation was not exploited as the highest percentage of the reported studies are comparative. There was an evident shortage of investigating the mechanism of the human perception for the built environment, hence, as highlighted in section 5, the reported studies had declined critical findings that can benefit the future built environment. This lack of input to the designers and decision makers is vital to address any regulations or standards that could improve the human experience within the built environment.

Although, the deep engagement between people and the built environment makes empirical research very difficult. For example, certain spaces or even colours can trigger many memories and feelings which vary extremely in humans as the research subject. This relationship complicates the measurements of the specific experience and how it impacts the brain, directly or indirectly. Therefore, the integration of psychology and neuroscience experts in any empirical study is critical to abstract the impact of certain design features on the human brain (Coburn et al., 2017).

However, the idea of an interactive built environment that keeps the user engaged and excited is not fictional. In 2002 at the Swiss Expo.02, Ada-an intelligent interactive space-was represented. The space was visited by over half a million visitors. The space was designed to interact with several users through light and sounds to keep them engaged (M. Arbib, 2012; Eng et al., 2003). With the recent advances in newly developed science, such as Bio/Neuro-Informatics and the implementation of new machine learning methods and analysis for user's brain mapping data, buildings could be customised to the users mental state (M. A. Arbib and Grethe, 2001; Hassabis, Kumaran, Summerfield, and Botvinick, 2017;

N. Kasabov, 2013; N. K. Kasabov, 2019).Such innovative approaches can lead to more explicit identification of the user experience in the built environment.

In conclusion, all the reviewed literature was consistent in signifying the variation of the impact of the built environment, and the impact of the evolved nature on the measured human brain waves. Using accurate scientific measures, such as fMRI and EEG, showed positive impacts on the human brain while in natural settings. On the contrary, the built environment has exhibited higher frustration and stress level as indicated by the measured brain activity. While there is a growing desire to document how the brain/mind reacts to different environmental stimuli and how that may benefit the field of architecture, engineering, and landscape design, very little is known at this time.

There was only one design element that was identified in the literature, curvature as an alternative to straight lines, which has a direct relation to brain activity (Banaei et al., 2017; Vartanian et al., 2015; Vartanian et al., 2013). Even though we can argue their use of VR or fMRI with only photos, these research efforts are the only ones that gave a direct input to designers that interior designs with more curvatures, higher ceilings and less straight lines showed higher excitement and engagement levels. Similar critical studies are required on a bigger scale, e.g., building designs and urban planning, to identify which features to include or exclude in the built environment regulations.

Only few studies have examined different urban designs with various functions, e.g., residential vs commercial, and their varied impact on the human state of mind (Aspinall et al., 2015; Hollander and Foster, 2016). This inclusion of the buildings' functions into the human measured experience is critical to identify the impact of the built environment on the human brain.

The reviewed litrerature has proved that a built environment with positive effects on the human brain can be reached by 1) Encouraging more research with advanced focus and specific scope into the mechanism and the design features; 2) More detailed research to simulate nature in the built environment; 3) Innovative designs with instant brain activity measurements that could link the building function with the measured state of mind. These might open the way to healthier surroundings that have positive impacts on the brain which will lead, in the long term, to psychological well-being.

Chapter 3 – Literature review: The brain response to indoor thermal comfort: from the thermal perception to the current indoor thermal comfort indices.

3.1 Prelude

As highlighted in section 1, due to the complexity of the subject, a further This study aims to critically review existing theories of ITC in comparison to the indices commonly used to measure it. Moreover, this review examines brain mapping studies to identify the neurophysiological significance of ITC within occupants' brains. The study discovers that the brain's response to thermal variations involves the activation of six distinct brain regions. Furthermore, the findings reveal that all brain Encephalographic (EEG) wave bands can be influenced by the thermal environment, subsequently impacting the occupants' state of mind.

However, this research also highlights the limitations of current thermal indices in thoroughly accounting for the impacts of perceived thermal comfort (PTC), as they often fail to adequately consider the neuropsychological effects of thermal sensation. Consequently, this study proposes a novel framework to incorporate the impacts of PTC into building performance assessments. By integrating the neuropsychological effects of thermal comfort, the proposed framework seeks to provide a more comprehensive understanding of the occupants' experience within indoor environments. This, in turn, will contribute to the development of more effective strategies for optimizing thermal comfort and enhancing occupants' well-being.

By conducting a critical review of existing theories, analysing brain mapping studies, and proposing a framework for incorporating PTC impacts, this research aims to advance the current understanding of the complex relationship between indoor thermal comfort and occupants' state of mind. The study's findings have significant implications for building design, operation, and management, as they underscore the importance of considering the neuropsychological aspects of thermal comfort in creating healthier and more comfortable indoor environments.

3.2 Introduction

Modern civilisation has urged humans to spend more than 90% of their daily lives inside buildings (Bluyssen, 2020; Zomorodian, Tahsildoost, and Hafezi, 2016). In principle, human mind perceives its surrounding built environment via several neurological paths, connecting all senses to the brain. The neural receptors interconnect through the peripheral neural channels and the central nervous system, to effectively integrate all these senses into our perception. This integration impacts all biological and cognitive activities (Bear et al., 2016; Papale et al., 2016).

The human central nervous system reacts to stimuli influencing our perception of Indoor Environmental Quality (IEQ), consists of four essential components, namely: Indoor Thermal Comfort (ITC), Indoor Air Quality (IAQ), aural, and visual comfort (Bluyssen, Janssen, Brink, and de Kluizenaar, 2011; Kishi, Norbäck, and Araki, 2020; Wong, Mui, and Hui, 2008). These, four components, include sub-parameters such as temperature, humidity, and air velocity that may directly or indirectly impact the occupants' satisfaction or sensation of comfort (Goldman, 1999; Guevara et al., 2021; Jiang, Wang, Liu, Di, and Liu, 2021; Mendell, 2003; WHO, 2015).

The measurement of IEQ is relative to the occupants' perception and often depends on the overall statistical significance of a selected sample (Földváry Ličina et al., 2018). Table 3.1 summarizes methods implemented to measure the IEQ and the occupant's comfort and dissatisfaction with the surrounding indoor environment (Bluyssen, 2004; Bluyssen et al., 2011).

*4 **Table 3.1:** Relevant research methodologies in IEQ*

Method	Example of Reported Studies	Description	Measured factors
Epidemiological approach	(Kishi and Araki, 2020; O'Lenick et al., 2019) (Johnson, Mavrogianni, Ucci, Vidal-Puig, and Wardle, 2011) (d'Ambrosio Alfano, Bellia, Fragliasso, Palella, and Riccio, 2019; Riley et al., 2016)	Questionnaires combined with biological measurements (e.g., blood, urine) creating physiological data representing the human body's reaction to external stressors	• Physiological changes. • Personal factors.
Field studies	(Bluyssen, 2020; Taleghani, Tenpierik, Kurvers, and van den Dobbelsteen, 2013) (Kotopouleas and Nikolopoulou, 2018; Ormandy and Ezratty, 2012) (Thai, Cândido, Asumadu-Sakyi, Barnett, and Morawska, 2019)	A general or a smaller sample of the public studied against environmental records.	• Subjects' behaviour. • Measured environmental parameters.

Laboratory Studies	(Lv, Su, Yang, and Wu, 2017; Song, Mao, and Liu, 2019) (H. Zhang et al., 2018) (Ismail et al., 2021; X. Lang, P. Wargocki, and W. Liu, 2022) (Čulić, Nižetić, Šolić, Perković, and Čongradac, 2021)	The subjects are exposed to controlled environmental parameters while their physiological and psychological behaviour are studied. New research is utilising machine learning algorithms to create human ITC models.	• Various factors. • Can vary from observation to brain mapping.

As shown in Table 3.1, most of these methods depend on sampling and rarely consider the variation of personal thermal perception over a larger population. Studies developed based on the adaptive thermal comfort theory have pointed out that the perceived thermal comfort varies depending on hedonic and adonic factors (Aizawa et al., 2019; Farrell et al., 2011; M. Humphreys, Nicol, and Roaf, 2015). In addition, these methods are often considered brief observations and are exclusive of the resulting impacts of IEQ on the occupants' perception. Hence, the relationship between the occupants' perception and the surrounding environment needs to be studied against changes in the IEQs' parameters using advanced measurements and analysis to establish a comprehensive framework for IEQ assessment. These correlations should result in an inclusive model, including the changes in surrounding parameters, of both the environment and the subject. The comprehensive analysis of these established relationships between the occupants' perception and the indoor surrounding environment forms the core concept of developing the indoor indices.

The occupants' psychology and physiology can be significantly impacted by parameters directly linked to indoor thermal such as temperature, humidity and air velocity (Ye Yao, Lian, Liu, and Shen, 2008). Recently, a significant number of research has been developed to investigate ITC from physiological perspectives, for instance, exploring the relationship between ITC and sweating, vasodilation, metabolism, and vasoconstriction (Huizenga, Hui, and Arens, 2001; Zheng, Chen, Li, and Chen, 2006).

However, the focus of these studies has been mainly limited to physiology, whereas the psychological impact was commonly excluded (R. J. de Dear et al., 2013; Dong, Zhao, Ren, Ge, and Chan, 2022; Ismail et al., 2021). Nonetheless, the findings of recent studies attested that thermal comfort can also affect the human brain and neural systems (Aizawa et al., 2019; Choi et al., 2015; Čulić et al., 2021; Lv et al., 2017; M. Wu, Li, and Qi, 2020). This indicates the necessity of developing a more comprehensive framework to identify the impacts of ITC on the occupants' perception of the ITC. Therefore, this paper approaches the literature aiming to answer the following research questions:

i) What is the current comprehension of ITC and PTC in literature? (Sections 3.2.2 and 3.3.1)

ii) What are the gaps between the actual PTC and the current ITC indices? (Sections 3.4.2 and 3.4.3)

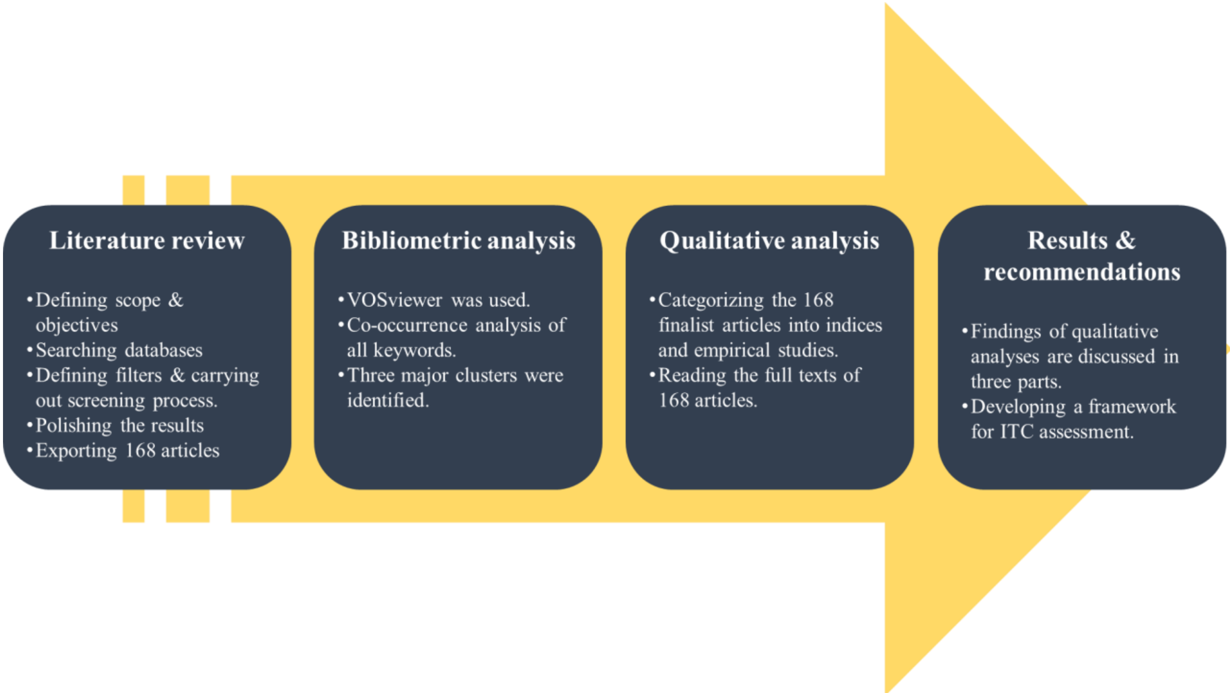
iii) How can PTC be integrated into the current ITC indices? (Section 3.5)

To achieve this, this paper conducts a thorough evaluation of the literature related to the physiological, psychological, and neurological mechanisms of thermal perception. The results are then compared to the thermal indices that are currently being utilised in building standards. Further, the results of these analyses are exploited to establish a comprehensive framework for future ITC assessments. the outcomes of this research can be beneficial to the future development of ITC indices, promoting the inclusion of occupants' PTC. The proposed framework is of a great importance to the built environment stakeholders, helping them to enhance the overall occupant experience and better fulfil the building functions.

3.3 Materials and method

3.3.1 Research approach

The overall methodological approach of this paper is illustrated in Figure 3.1. The initial stage involved a comprehensive search through multiple scholarly databases, namely Scopus, Web of Science, ProQuest, and Google Scholar. The keywords used for conducting the initial search encompassed a wide range of terms corresponding to the objectives of this paper, including thermal comfort, thermal perception, adaptive thermal comfort, thermal comfort index, thermoregulation, Electroencephalograph (EEG), MRI, fMRI, brain mapping, neuro, and nervous system. As a result, 248 materials published between 1970 and 2022 were identified as the first pool that covers most of these keywords. It is noteworthy that the search only accounted for types of materials identified as “article” and “review”. Further, studies published in non-English languages and those retrieved from non-peer-reviewed sources were excluded. This led to reducing the collected studies to 202.

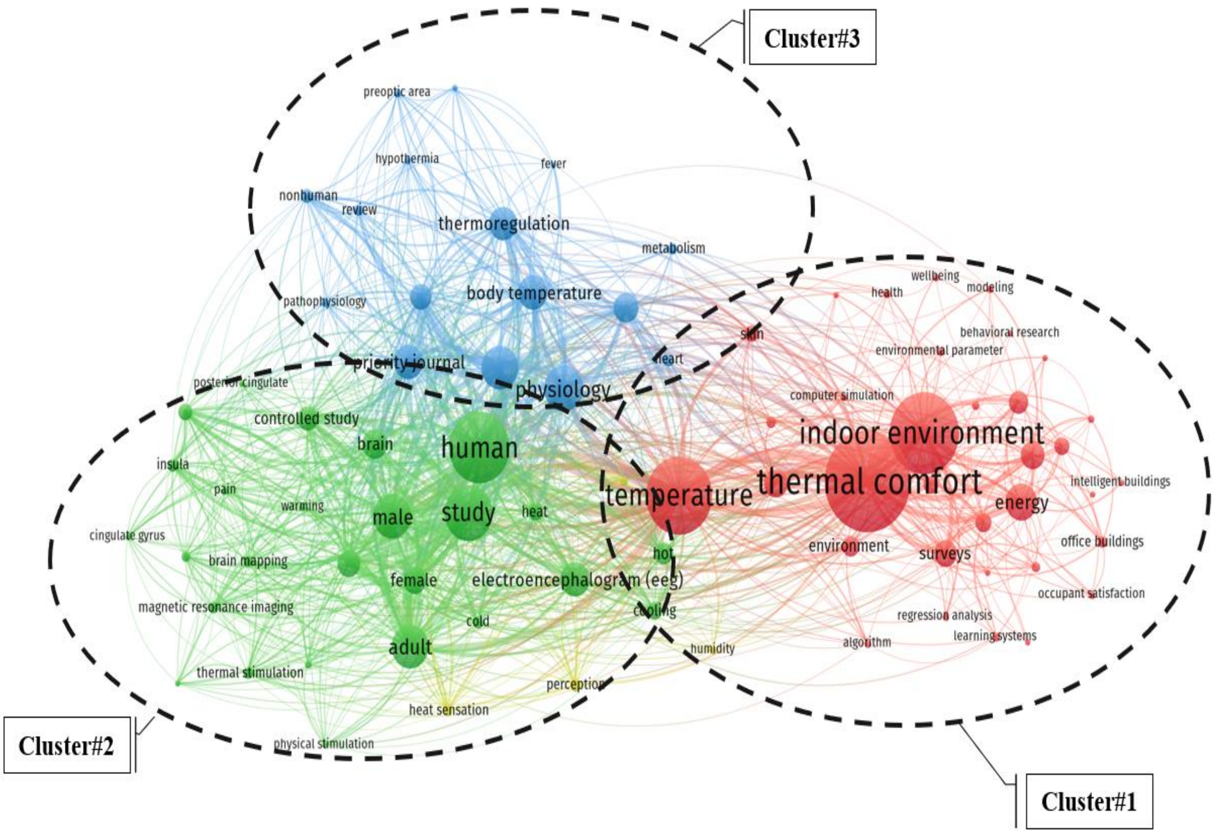


*10 **Figure 3.1**: The methodological approach*

In addition, reference lists of identified materials were examined to ensure that no research with relevance to the scope of this study was excluded. Using similar keywords, a grey literature search was also conducted via Google’s general search engine, aiming to identify materials suitable for inclusion, such as international standards, governmental reports, or policy statements. These additional exercises resulted in identifying 14 more studies, increasing the total number of publications to 216. Afterward, an individual reading-selection procedure was carried out by reviewing the titles and abstracts of identified materials to ensure that only those corresponding to the scope and objectives of this study were selected for detailed examination. Hence, materials that failed to directly address indoor thermal comfort were excluded. This consideration resulted in decreasing the number of retrieved publications to 168. Thus, these materials were selected for the final assessment.

3.3.2 Bibliometric analysis of the literature

The literature's keywords can be analysed to identify the main research domains across a discipline (Omrany et al., 2022). The keyword analysis assists with unveiling intertwined associations of research topics/sub-topics within a certain domain (Omrany et al., 2022). In this approach, the calculation is performed based on the frequency of keywords co-occurring in publications and the strength of correlations among them (Omrany et al., 2022; Sharifi, 2021). The outcomes achieved via bibliometric analysis, in tandem with critical literature analysis can lead to a comprehensive understanding of the research area. Therefore, this paper utilises VOSviewer software to examine the nexus of keywords' co-occurrence within the selected 168 studies. To this end, all keywords including keywords inputted by authors and those indexed by sourcing journals (e.g., keywords plus) were exploited to carry out the co-occurrence of keyword analysis. Figure 3.2 illustrates the result of this analysis performed for a minimum threshold of eight keywords. In this figure, the size of each node corresponds to the number of times that a given keyword appeared in the literature. In this figure, the close placement of nodes implies strong relationships between keywords while the strength of their connections is represented by the thickness of the links connecting them.



11 ***Figure 3.2:*** *Visualising co-occurrence analysis of keywords.*

Table 3.2 shows fifteen keywords with the highest co-occurrence values and their attributed link strength. These terms have received more attention and are strongly associated with other keywords. As shown in Figure 3.2, the co-occurrence analysis of keywords identified three major clusters. It is perceived that keywords such as "temperature", "thermal comfort", "adaptive thermal comfort", "built environment", and "thermal sensation" from cluster 1; "human", "brain", "adult", "female", "male" and "EEG" from cluster 2, and "physiology", "subject", "skin temperature", "thermoregulation", "body temperature", and "thermo-sensing" from cluster 3, are located close to the borders of the clusters, implying that these domains of publications are cross-cutting with solid connections with other clusters.

5 ***Table 3.2:*** *Fifteen keywords with the highest co-occurrence.*

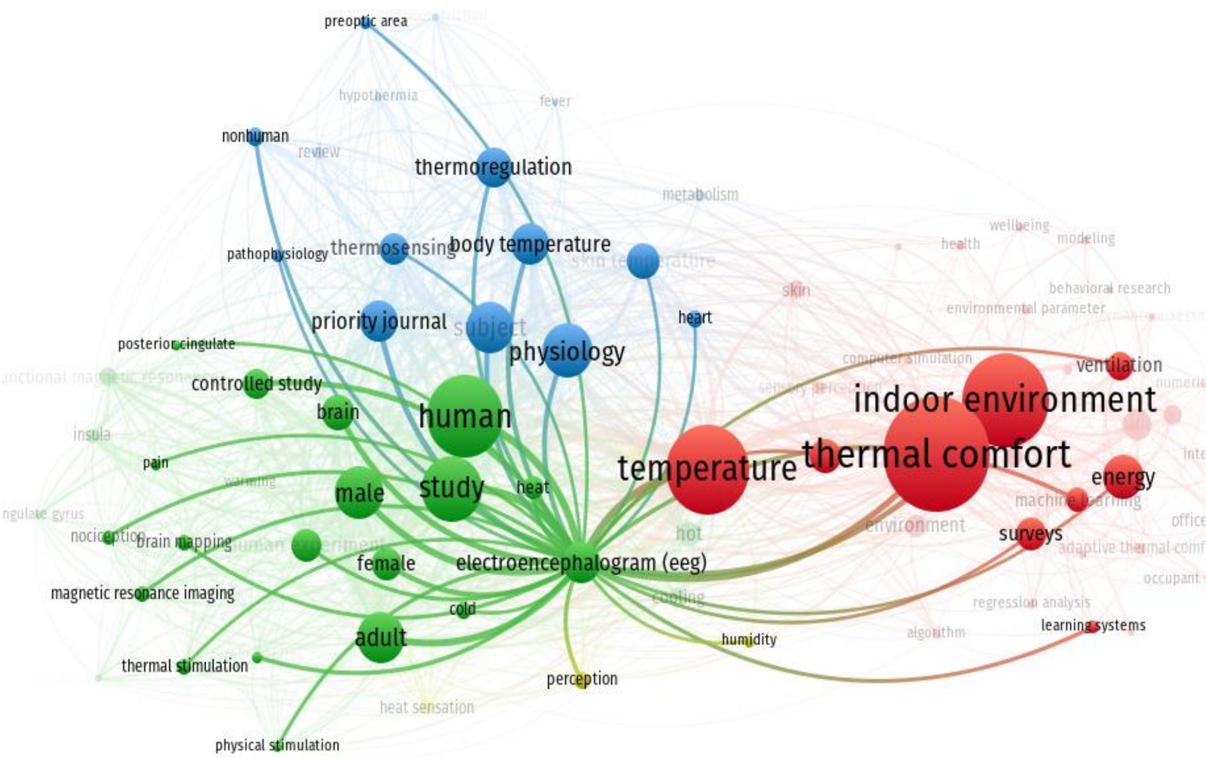
keywords	Occurrences	Total link strength
Thermal comfort	77	413

Indoor environment	62	282
Temperature	59	490
Human	55	532
Physiology	35	321
Adult	33	393
Subject	33	388
Energy	28	165
Body Temperature	27	305
Electroencephalogram (EEG)	27	204
Thermoregulation	25	253
Brain	23	239
Thermal sensation	22	190
Human Experiment	21	292
Survey	21	135

Among all reviewed studies, buildings' energy savings and reduction of environmental impacts associated with building operations have received high attention, mainly due to the global efforts being undertaken to mitigate climate change (O'Lenick et al., 2019; M. Shan and Hwang, 2018). This has subsequently shifted the dominant stream of research towards exploring solutions for improving energy efficiency in the building sector (Hensen and Lamberts, 2012; Z. Wang et al., 2018). Most of the reviewed literature focused on reducing the total energy demand, building envelope, recovery/reduction of the building wasted energy, optimisation of utility consumption, etc. (de Wilde, 2019; Jain, Burman, Robertson, Stamp, Shrubsole, Aletta, Barrett, et al., 2020; Mallory-Hill, Preiser, and Watson, 2012).

Further, the bibliometric analysis results indicate that the actual perceived thermal sensation or the occupants' PTC, have given less attention in the literature. This was evident in figure 3.2 for keywords such as "Occupant Satisfaction", "Perception", and "Adaptive Thermal Comfort", where their node sizes were dwarfed by other keywords that are less significant compared to the occupant experience or PTC, e.g., "Energy". The bibliometric analysis further implied that methods based on epidemiological approach, have been dominantly utilised by the current body of literature. This is demonstrated in Table 3.2 by the relatively higher values of occurrence for the terms "Physiology," "Body Temperature," and "Thermoregulation.".

The keywords associated with brain mapping studies and neuroscience, e.g., "Brain Mapping", "Magnetic Resonance Imaging", and "EEG" had relatively moderate/medium size nodes. This implies that these measurement studies are still developing, compared to older methods in the body of literature. However, examining figure 3.3, the placement of the "EEG" node indicates strong central relationships between all other keywords. This indicates that EEG-based studies have the potential for linking the fundamental parameters of PTC, as further discussed in section 4.



*12 **Figure 3.3:** Visualising co-occurrence analysis of keywords with focus on EEG.*

3.4 Results of the critical review

3.4.1 Indoor thermal comfort

ITC research combines various sciences such as physiology (Liu, Lian, and Liu, 2008; M. Wu et al., 2020), mechanical engineering (Jing, Lei, Wang, Song, and Yan, 2019; Kampelis et al., 2017), building design (J. Li et al., 2019b) and psychology (R. J. de Dear et al., 2013). Various definitions have been presented in the literature to characterise the concept of thermal comfort, each focusing on specific criteria (Table 3.1). For instance, ASHRAE described ITC as “the condition of mind that expresses satisfaction with the thermal environment” (Heating, Refrigerating, Engineers, and Institute, 2004). In another expression, Enescu (2017) mentioned that ITC can be used to characterise the thermal state of occupants within a given thermal environment. In general, the universal temperature ranges from close to absolute zero (–273°C) to more than 1,000,000°C (Romanovsky, 2018). Nevertheless, the liveable temperature of most animals is between a minuscule percentage of this range (~ 4%), approximately between 0 and ~ 45°C. Most organisms fail to survive at a body temperature lower than 0°C due to cell dysfunctions. Analogously, life is considered almost impossible at a body temperature of more than 45°C, since the enzymes responsible for catalysing biochemical reactions begin to denature at such temperature (Leon and Bouchama, 2011; Lepock, 2003; Romanovsky, 2018). Even below 45°C, the temperature can be fatal for living creatures due to brain cell disintegration. This is echoed in the findings of Matsumi et al. (1994), that reported thermal damage in a healthy monkey brain due to its exposure to 44°C for an hour.

*6 **Table 3.3:** Summary of the ITC definitions.*

Description of TC	Purpose of TC	Reference

Perceived condition of satisfaction with the surrounding environment	• Creating a satisfactory condition for the occupants, • Managing the energy load, and • Developing and implementing technical standards	(R. J. de Dear et al., 2013); F. Nicol (1993); (Omer, 2008; Sayigh and Marafia, 1998)
A state of mind that reflects thermal equilibrium with the surrounding environment	• Setting the indoor environment for the occupants • Enhancing the indoor air quality • Achieving energy savings. • Reducing the building's environmental impact resulting from CO2 emissions • Improving the occupants' work efficiency • Continuously improving the buildings' standards	(Ormandy and Ezratty, 2012; Oseland and Humphreys, 1994; Taleghani et al., 2013)

In terms of psychological perception, the occupants' perception of external thermal stimulation consists of two main components: thermal sensation and thermal comfort (Hensel, 1981). Thermal sensation is defined as the subjective reaction to the external temperature setting within the surrounding environment, triggered by the warm or cold neural receptors scattered on the human skin (R. J. de Dear et al., 2013). Thermal comfort is also described as the correlation of objective thermal sensation and subjective perception of the surrounding thermal environments (Nakamura et al., 2008).

In recent years, ITC has attracted a significant research focus from neurophysiologists and industrial designers' academics (Arakawa Martins, Soebarto, and Williamson, 2022; Kishi et al., 2020; Zhu, Liu, and Wargocki, 2020). Nevertheless, individual physiology could fluctuate substantially amongst the subjects. These variations have an impact on the perceptions of the ITC, i.e., high metabolic rate or high body fat can cause a warm sensation, which impacts empirical studies and subjective classification (Huizenga et al., 2001; M. Wu et al., 2020). However, scientific interest in such a matter has been developing to accurately indicate and predict thermal comfort.

3.4.1.1 Development of Indoor Thermal Comfort indices

The first reported Thermal Comfort hypothesis was put forward by a British doctor, Charles Blagden, in 1774 (Blagden, 1775). From a physiological perspective, the very early endeavour to understand thermal regulation of the body temperature can be traced back to Charles Blagden (1775) using a thermometer in a warmed room. The experiment focused on the subject endurance for higher temperatures. In the 1930s, Gagge focused his research on the mechanism of heat exchange between the animal body and the surrounding environment (Gagge, 1937; Gagge, Burton, and Bazett, 1941; Gagge, Winslow, and Herrington, 1938).

From an engineering perspective, the complex thermometer was developed by Sir Leonard Hill, who measured body heat transfer for the first time in 1914 (Hill, Flack, and Griffith, 1914). Later, the idea put forward by Sir Leonard Hill for integrating the impacts of air temperature, air velocity, and mean radiant temperature led to the developing of the equivalent temperature (Teq) (Song et al., 2019). Table 3.4 shows the progress of ITC indices (Taleghani et al., 2013).

*7 **Table 3.4:** Timeline of the development of ITC indices in buildings.*

Year	**Index**	**Reference**
1945 - 1959	Thermal acceptance ratio (TAR)	(Robinson, Turrell, and Gerking, 1945)

Year	Index	Reference
1960 - 2000	Predicted 4-h sweat rate (P4SR)	(Wyndham, 1970)
	Oxford index (WD)	(Lind and Hellon, 1957)
	Discomfort index (DI), Modified in 1999 to (MDI)	(D. Moran, Shapiro, Epstein, Matthew, and Pandolf, 1998; Thom, 1959)
	Cumulative discomfort index (CumDI)	(Tennenbaum, Sohar, Adar, and Gilat, 1961)
	Predicted mean vote (PMV)	(Fanger, 1970)
	Standard effective temperature (SET)	(Gonzalez, Nishi, and Gagge, 1974)
	Physiological equivalent temperature (PET)	(Höppe, 1999)
2001-2018	Environmental stress index (ESI)	(D. S. Moran et al., 2001)
	Universal thermal climate index (UTCI)	(Jendritzky, Maarouf, and Staiger, 2001)
	Personal comfort models	(Joyce Kim, Zhou, Schiavon, Raftery, and Brager, 2018)

Prior to 1960, the main feature of the ITC indices' earlier period, was the physiological measurements of the subjects' bodies that reflected thermal acceptance (e.g. skin/body temperatures, pulse rates, blood flows, etc.) (Lind and Hellon, 1957; Liu et al., 2008). The development of these indices often involved or depended on measuring the thermal equilibrium, between the subject body and the surrounding environment.

The middle period, from 1960 to 2000, witnessed extensive experimenting and data collection aligned with the development of the control climate chamber and the communication boom (Brager and de Dear, 1998; R. De Dear, Leow, and Ameen, 1991). The maturity of data analysis and computing methods within this period significantly contributed to developing the most widely used index, the PMV model (M. A. Humphreys and Fergus Nicol, 2002; Olesen and Parsons, 2002; Park and Nagy, 2018). These indices have also introduced psychological questionnaires to measure the perceived thermal comfort (Nikolopoulou and Steemers, 2003).

The latest period, 2001 to 2018, has focused on the personal perception of the thermal environment (Jungsoo Kim and de Dear, 2018; Joyce Kim et al., 2018). These indices depended more on measuring and analysing the subjects' observed behaviour and collected psychological data. This period has introduced and widely used the standardised "comfort vote" as a descriptive scale following ASHRAE (J. F. Nicol and Humphreys, 2002; The American Society of Heating, 2004).

Currently, a significant number of indoor thermal comfort studies are developed based on the (PMV) model (Broday, Moreto, de Paula Xavier, and de Oliveira, 2019; Lin, Chow, Tsang, Chan, and Fong, 2005; G. Zhang, Zheng, Yang, Zhang, and Moschandreas, 2007; S. Zhang, Cheng, Oladokun, Wu, and Lin, 2020).

3.4.1.2 Predicted Mean Vote (PMV)

Fanger Ole established the PMV model in the late 1960s (Fanger, 1970). PMV, as described in International Standard ISO 7730 (ISO, 1994; E. Iso, 2005), is probably the most commonly used index of thermal comfort to evaluate modest indoor thermal environments (Földváry Ličina et al., 2018; Taleghani et al., 2013; Zomorodian et al., 2016). It was established based on the steady-state heat transfer model, it was then standardised versus Nevins' and McNall's records of the thermal sensations of many subjects obtained during several studies in a climatic chamber (McNall, Jaax, Rohles, Nevins, and Springer, 1967). The PMV model has also been integrated into the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55–Thermal Environmental Conditions for Human Occupancy (Hasan, Alsaleem, and Rafaie, 2016). This integration has resulted in furthering the widespread application of the PMV model (Broday et al., 2019). The PMV model describes the thermal sensation related to the surrounding thermal conditions. Nevertheless, it excludes the physiological and subjective reactions to the thermal environment. As highlighted in Table 3.5, most PMV variables are external or physiological factors (Hasan et al., 2016; J. F. Nicol and Humphreys, 2002). PMV forecasts the likely comfort vote based on the ASHRAE scale of subjective warmth using the following scale:

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly Cooled
-2	Cool
-3	Cold

The comprehensive climate chamber studies constituting the PMV model exhibited that the occupants' thermal sensation depends on the applied thermal load to the thermoregulatory system (Földváry Ličina et al., 2018). PMV model could forecast thermal awareness concerning several variables such as activity, clothing, and the main conventional thermal variables of air temperature, mean radiant temperature, air velocity and humidity, see Table 3.5 (J. F. Nicol and Humphreys, 2002) (E. Iso, 2005; Ncube and Riffat, 2012; F. Nicol, Humphreys, and Roaf, 2012).

*8 **Table 3.5:** Categorisation of PMV variables.*

Variable	**Unit**	**Category**	**Occupant dependant /Independent**	**Comments**
Metabolic rate	W/m2	Physiological	Occupant dependant	Varies widely; however, average/default values are often used
Effective Mechanical power	W/m2	Physiological	Occupant dependant	Depends on the activity. Often standardised based on space function
Cloth insulation	m2.K/W	Behavioural	Occupant dependant	Depends on the occupants' choices. Often standardised based on space function
Clothing surface area factor	-	Physiological	Occupant dependant	Depends on the body type and activity
Air Temperature	°C	External	Independent	Surrounding environment

Mean Radiant temperature	°C	External	Independent	Surrounding environment
Air Velocity	m/s	External	Independent	Surrounding environment
Water vapour partial pressure	Pa	External	Independent	Surrounding environment – Humidity
Convective heat transfer coefficient	W/m. k	External	Independent	Surrounding environment
Clothing surface temperature	°C	External	Independent	Surrounding environment

In essence, PMV depends on numerous gauged and estimated variables. Recently, several tools and programmes, such as Delta Ohm Thermal Microclimate HD32.1, have been developed to enable accurate measurements of PMV and predicted percentage of dissatisfied (PPD) based on data gathered via appropriate sensors as well as the data provided by users (Asere, Mols, and Blumberga, 2016; Gendelis, Jakovičs, and Ratnieks, 2017). Nonetheless, due to subjectivity, the users' data inputs may undermine the accuracy of achieved results. For instance, Olesen and Parsons (2002) reported that variables such as metabolic rate (M) or the clothing insolation factor (I_{cl}) could impact the PMV accuracy, as shown in Table 3.6 (Olesen and Parsons, 2002). These two factors are the only individual dependent/human factors of the PMV. The offset resulting from their variations indicates inadequacy in predicting the occupants' perceived thermal comfort.

9 Table 3.6: The effect of the precision of estimating the metabolic rate and clothing insulation on PMV and PPD values.

M (W m^{-2})	**I_{cl} (m^2 °C W^{-1})**	**PMV Score (deviation)**	**PPD (%) (deviation)**
50	0.130	−1.0	27.7
58	0.155	0.0	5.0
66	0.180	0.4	8.8
85	0.130	0.5	10.5
100	0.155	0.9	22.6
115	0.180	1.2	36.4

t_a=t_r=24 °C; P_a=1000 Pa; v=0.15 m s^{-1}.

3.4.2 The human factor of thermal comfort

The perceived thermal comfort is subjective to the occupant's experience, influencing the occupants' satisfaction with the surrounding environment. The occupants' perception of thermal comfort can be discussed in connection with several physiological and psychological factors that impact the human thermoregulation system such as the sense of control or cognitive activity and the peripheral environment (Aizawa et al., 2019; Foo and Mavrogianni, 2018; Romanovsky, 2018; X. Zhou, Zhu, Ouyang, and Zhang, 2011). Several studies attempted to investigate ITC by exploiting physiological parameters, namely metabolism, sweating, vasodilation, and vasoconstriction to trace the thermal sensation from its initial receptor, namely the skin (Afshari, Moradi, Angali, and Shirali, 2019; Cheng, Lee, and Huang, 2018; Huizenga et al., 2001; Zheng et al., 2006). These studies have been mainly developed based on the premise that the mechanisms of ITC can only be comprehended through physiological analysis. Hence, they tend to rely on measuring the subjects' physiological functions (e.g., skin/body temperatures, pulse rates, or blood flows) to understand thermal comfort. Nevertheless, the adoption of such an approach is exclusive to the occupant's actual perceived experience and the variation in their personal thermal satisfaction preferences.

The increasing trend of research focusing on the perceived thermal sensation has led to the development of a host of studies investigating thermal sensation from psychological and neurological perspectives. For instance, the skin which is the first receptor of the surrounding thermal environment is covered by a significant number of thermoreceptors and has been the subject of several studies in both steady and dynamic states (Bulcao, Frank, Raja, Tran, and Goldstein, 2000; Z. Wang, He, Hou, and Jiang, 2013; Yang, Li, Liu, Tan, and Yao, 2015). The skin instigates the thermoregulation response which is a critical factor in behavioural comfort (Aizawa et al., 2019; B. Weiss and Laties, 1961). Skin also substantially impacts comfort levels and the thermal perception of the occupants (Frank, Raja, Bulcao, and Goldstein, 1999; Tabarean, 2018). Furthermore, skin temperature and heart rate fluctuation have been considered ITC indicators since they are measurable and can identify the neural channels for thermal sensation (Liu et al., 2008; Y Yao et al., 2009).

The skin is covered by two main thermal neuroreceptors types, namely cold and warm (Kandel and Mack, 2013). Both of these thermal neuroreceptors are connected from the peripheral neural system to the subsequent cold and warm neural cells in the anterior hypothalamus within the central neural system (Kandel and Mack, 2013; Tan et al., 2016). The anterior hypothalamus is considered the central part of the brain responsible for thermoregulation, responding to changes in the surrounding thermal environment and maintaining a regular body temperature by stretching or constraining the vessels responding to thermal change (Romanovsky, 2018).

The functional brain activities recorded by neuroimage, and electrophysiological devices have a significant advantage in measuring the perceived thermal comfort in different thermal environments. For example, Kanosue et al. (2002) utilised functional magnetic resonance imaging (fMRI) to measure the configuration of regional brain activation during the cooling of the entire body. They reported an increase in the measured fMRI activation, including the bilateral amygdala, when exposed to cold conditions. Similarly, Farrell et al. (2011) used positron emission tomography (PET) to establish a relationship between the measured changes in the posterior part of the cingulated cortex and the degree of the hedonic factor of thermal sensation. They reported similar brain activation in the nervous system in associative, limbic, paralimbic, and somatosensory cortices. Additionally, Kanosue et al. (2002) and Farrell et al. (2011) identified a vital role for the posterior mid-cingulate cortex (pMCC) in the integration of temperature signals from the thermal receptors in the skin and the body's core temperature.

The EEG was used to examine the correspondence of the cerebral to the thermal stimulus. The relative global frequency bands in EEG (i.e., alpha and beta bands) were reported to fluctuate in response to the subject's thermal sensation in an ambient thermal environment (Ye Yao et al., 2008). Few EEG-based studies further explored the EEG recordings during thermal pain (Dowman, Rissacher, and Schuckers, 2008; Shao, Shen, Yu, Wilder-Smith, and Li, 2012) and ambient thermal conditions (Chang, Arendt-Nielsen, and Chen, 2005). Several studies also reported the same fluctuation in the EEG power ranges (Chang et al., 2005, Dowman et al., 2008) and various structural dispersal of the cortical sources (Shao et al., 2012, Wang et al., 2015) accompanying the thermal provocations. These efforts indicated the direct variation of the neuron's activation magnitude over various brain regions. Most of these neurophysiological studies demonstrated a neurophysiological correlation to the mechanism of ITC in the peripheral and central nervous systems. However, these findings were limited to the direct neurological activation of external thermal stimulation. Recently, few studies have integrated the measured brain activation into the occupants' perceived experience, e.g., satisfaction, cognitive performance, and state of mind (Dong et al., 2022; X. Lang et al., 2022; Y. Wu et al., 2022). These studies have identified ITC parameters as more significant, in the subject performance, than other indoor environmental quality parameters.

In this review, it becomes evident that most studies endeavoured to explore physiological parameters to understand the skin's thermal sensation. Nevertheless, the review of recent studies has shown that the neurological connection from the skin, as the first receptor to the central nervous system, should be considered from psychological and neurological points of view. Several recent studies have also reported fluctuation appeared in several areas of human brains, identifying the central brain regions and their responses to thermal environments (Aizawa et al., 2019; Lv et al., 2017; Mansi et al., 2021; Nakamura et al., 2008; M. Wu et al., 2020). This further underlines the necessity of integrating the measured brain activity to interpret the perceived thermal comfort and further quantifying the ITC/PTC in terms of measured brain activity.

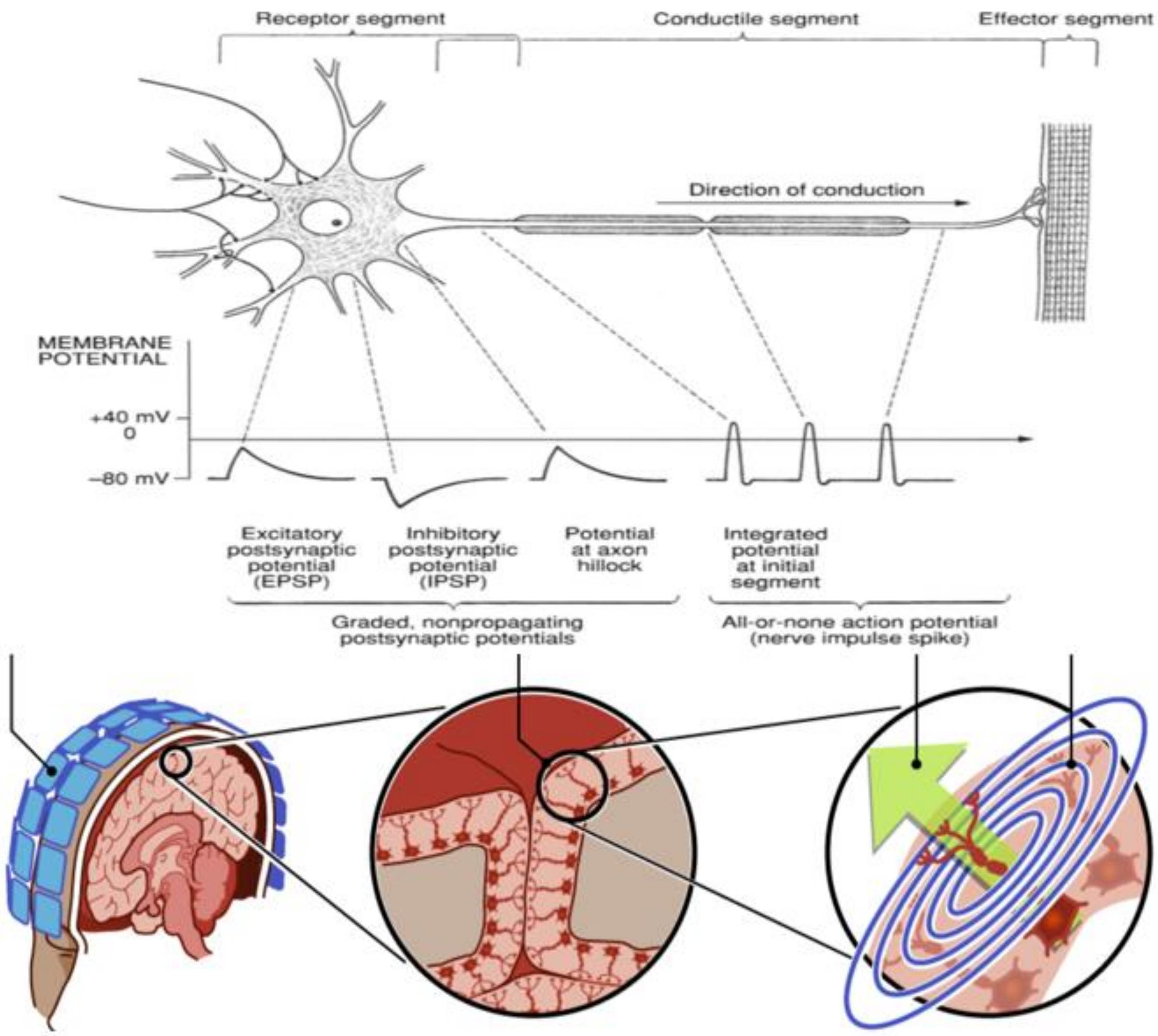
3.4.2.1 Preoptic area/anterior hypothalamic (POAH)

The medial preoptic/anterior hypothalamic area (POAH) is one of the mammalian brain's most critical thermosensitive areas (Madden and Morrison, 2019; Szymusiak, 2018). Besides its significant function in thermoregulation, POAH neurons contribute to wakefulness and the quality of sleep (Alam, Szymusiak, and McGinty, 1995; Tan and Knight, 2018). Thermosensitive neurons' existence in POAH was first discovered in the early 1960s (Matsumura, Nakayama, and Ishikawa, 1984). However, researchers recently reported that thermosensitive neurons also exist in several regions of the neural system, e.g., the spinal cord, the midbrain, and the medulla oblongata (Aizawa et al., 2019; Bokiniec, Zampieri, Lewin, and Poulet, 2018; Madden and Morrison, 2019).

Conventional neurological studies revealed that non-targeted stimulation of POAH cells could trigger intensive thermoregulatory reactions, e.g., sweating and panting, resembling the responses of heating the whole subject’s body (Tan et al., 2016). The integration of these synaptic changes impacts the brain's overall frequency, which extends to the subject’s state of mind (Lv et al., 2017), and their signal can be traced across the central nervous system.

3.4.2.2 Thermo-sensitivity in the central neuro system

Neurons communicate through electrical signals conveyed along axons and dendrites (Kandel and Mack, 2013). When the populations of neurons in the brain are synchronously triggered, their electrical signals can be recorded via electrodes placed on human scalps (Bermudez-Rattoni, 2007). For example, when we perceive a picture, a particular population of neurons in our brains are triggered by this picture. This response can be measured as a variation in voltage at the scalp before, during and after perceiving the picture (Milner and Rugg, 2013). One of the most used methods to detect these signals is EEG, which records and amplifies these electrical signals over time (Gegenfurtner et al., 2017; Kandel and Mack, 2013; Misulis, 2013; Nidal and Malik, 2014), as illustrated in Figure 3.3.



*13 **Figure 3.3**: Action potential signal and its detection over the brain.*

The top is a neural cell structure with the action potential signal types travelling via the axon. The bottom is the detection of the signal reaching the cortex (Kandel and Mack, 2013; Noback, 2005).

EEG is the most medically used recording method for brain function studies (Alarcão and Fonseca, 2019). Four primary regular rhythms are recorded by EEG scanners: alpha (α), beta (β), delta (δ) and theta (θ). Those rhythms are categorised by frequencies and amplitudes shown in Table 3.7 (Thakor and Tong, 2004) (Misulis, 2013; Nidal and Malik, 2014).

*10 **Table 3.7:** Major Brainwaves and their detections in thermal response studies, recorded by EEG and their indications.*

Wave	**Range**	**Mental state indication**	**Manifestation**	**Reported thermal response**
Alpha (α)	7-13	Disengagement, relaxed, disentangled	They appear spontaneously when: relaxed or during inactive mental conditions. They are often recorded when eyes are closed and are usually detected in the occipital regions.	(Chang et al., 2005; Dowman et al., 2008)

Betta (β)	13-30	Engagement, focused, computing	They have smaller amplitude compared to alpha waves. They intensify during cognitive computations, anticipation, or anxiety. They are often detected in the central and frontal brain regions.	(Shao et al., 2012)
Delta (δ)	0.5–4	Sleeping, unconscious	They are usually recorded during deep sleep. Based on the recorded rhythm, location and morphology, the Delta band could be natural during slow-wave sleep or indicates an abnormality in case of brain tumours.	(Lv et al., 2017)
Theta (θ)	4–7	Lower Range: Unconscious, creative inspiration. Upper range: Frustration, dissatisfaction	They are usually recorded in a deep sleep. They are significant during early life and childhood. For awake adults, increasing theta activity indicates abnormality or brain conditions, e.g., epilepsy.	(Chang et al., 2005)
Gamma (γ)	> 30	Attention, cognition, perception	Its lower rhythmic range (30-60 Hz) was considered insignificant until the 1990s. This Gamma band range drew many research interests after they were reported to be critical for connecting the stimulus to a specific perception. Various preceding studies reported Gamma correlations to different sensory activities and to various cognitive activities, e.g., during the perception of all sensory stimuli. The upper rhythmic ranges of Gamma (80 or 120 Hz and above), also referred to as epsilon rhythms, were reported in both human and animal Electrocorticographic (ECoG). It is often related to chattering action potentials.	(Dowman et al., 2008)

In response to thermal changes, the central nervous system triggers various responses of counter-regulatory neural signals to maintain the average body temperature throughout the change (Madden and Morrison, 2019; Romanovsky, 2018) via different means such as involuntary responses (thermogenesis, vasodilation, and sweating) or behavioural responses (warm or cold pursuit). These neurological signals cause EEG measurable frequencies to vary (Madden and Morrison, 2019; Tan et al., 2016). Quantifying the variation of these signals' magnitude and locality against a change of the external thermal stimuli using adequate brain mapping techniques can accurately estimate the level of human comfortability (Mansi et al., 2021; Zhu et al., 2020).

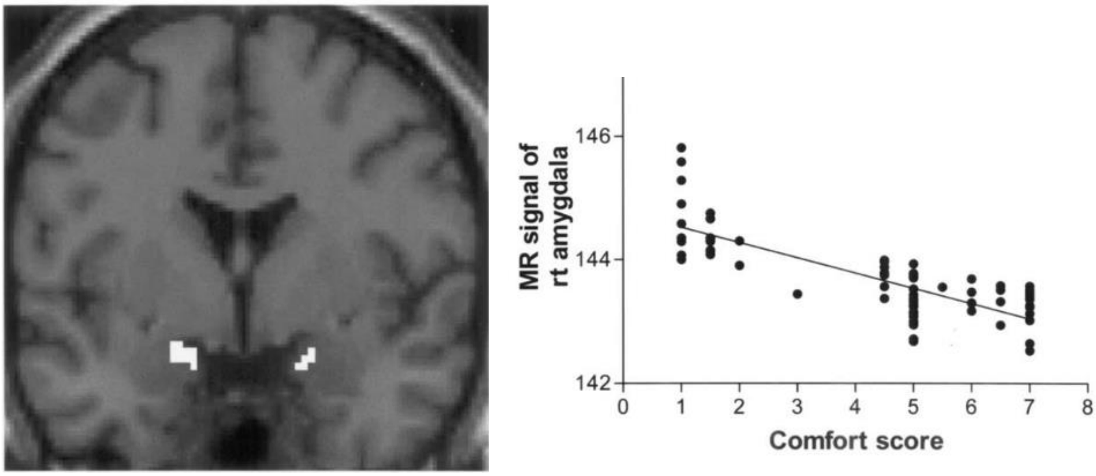
The retrospective studies suggested that circadian variations in the eternal brain temperature may result in variations of the EEG frequencies (Deboer, 2002; Deboer and Tobler, 1995). This further leads to affecting the EEG power density ranges. However, this claim was discarded by early experiments carried out by Kanosue et al. (2002), which revealed that thermal signals received from the skin's surface were conveyed to various areas within the cerebral cortex (Aizawa et al., 2019). The general state of mind or mood may be impacted by the perceived thermal sensation, which may be detectable by the brain's EEG recording rather than by local variations in brain temperature. This broadens the research focus to include brain mapping in thermal comfort studies.

3..4.3 Brain mapping and thermal comfort

There are several methods and techniques to measure the impact of an external stimuli on the brain. These measurement methods can be generally categorised into two main groups (Duffau, 2011; Tovée, 2008);

- Structural imaging: this technique provides a static picture of the brain structure, e.g., Computerized Tomography (CT), Magnetic Resonance Imaging (MRI) and Water Diffusion MRI (dMRI).
- Functional imaging: this technique provides momentary functional information of the brain by measuring the cellular activities across the brain regions, e.g., Positron Emission Tomography (PET), Functional MRI (fMRI), Electro-Encephalography (EEG), Magnetic Encephalography (MEG), Transcranial Magnetic Stimulation (TMS).

Functional imaging is widely used in the thermal comfort field due to its capacity for providing direct coloration between the momentary external changes in the environment and the subject brain activities. These measured magnitudes and locality of the brain activities (as an uncontrolled variable) can be analysed against the controlled changes in the thermal environment. In an early attempt, Kanosue et al. (2002) investigated the brain's response to thermal comfort using fMRI to record the human brain during entire body cooling. The results showed that neural signal activation could be intensified during cold discomfort (see Figure 3.4).



*14 **Figure 3.4**: The recorded fMRI signal intensity of the right amygdala Vs the thermal comfort score.*

(Left) The active region with significant variation of BOLD (blood-oxygen-level-dependent) signals. (Right) Significant variation in the right amygdala was recorded vs the comfort score and adopted from (Kanosue et al., 2002).

Kanosue et al. (2002) was the first study to report the amygdala activation due to thermal variation using functional brain mapping. However, Kanosue et al. (2002) failed to identify any significant signal intensity in earlier reported brain regions, e.g. the anterior and posterior cingulate gyrus, the anterior and posterior insula, the thalamus and the primary SI and secondary SII sensory cortices. Table 3.8 summarises specific studies that investigated these relationships.

*11 **Table 3.8:** Summary of the significant thermal comfort studies using brain mapping technologies.*

Study/Region	Scope	Findings
Becerra et al. (1999) / N America	Brain activity was studied with (fMRI) following thermal stimulation of (42-46°C).	• fMRI activation in brain areas including (the thalamus, somatosensory cortex, cingulate gyrus, precentral gyrus, and cerebellum)

		• Subthreshold signal changes were noted in the amygdala and hypothalamus.
Chang et al. (2005) / Europe	Investigation into the relative EEG variations of warm vs. cold local stimulus	• Different patterns of EEG recordings against thermal (Cold/Warm) stimulations • Theta activities significantly declined in the contra-stimulus frontal region in cold stimulation. • The Alpha and Theta bands intensified extensively afterwards cold stimulation. The delta and alpha bands variation were consistent in the contra-stimulus hemisphere throughout the thermal stimulations.
Dowman et al. (2008) / N America	Pain-related cortical activation during tonic cold pain condition	• In clod pain, the alpha band amplitude declined in the contralateral temporal region and intensified in the posterior region. • On the other hand, the gamma band amplitude increased across most of the recording electrodes. This could be increased in artifacts.
Ye Yao et al. (2008) / China	EEG recordings during various air temperatures of (21 °C, 24 °C, 26 °C and 29 °C) against surveyed PMV in accordance with the ASHRAE.	• All EEG bands: Gamma (δ), Theta (θ), Alpha (α) and Beta (β) have recorded variation against the thermal sensations. Indicating that EEG recordings can reflect the actual perceived thermal sensation.
Farrell et al. (2011) /Australia	PET activation patterns related to the experience of alliesthesia	• PET recordings analysis has identified the significant part of the cingulate cortex in the hedonic factor of processing external thermal stimuli. • Evaluations of the hedonic dimension of thermal sensation were interrelated and were analysed against the recorded brain activation maps.
Shao et al. (2012) / Singapore	Electrocortical responses to cold pain recorded by EEG to establish possible electrocortical indices of acute tonic pain.	• Significant difference in EEG band power in Cold Pain (CP) and No Pain (NP) conditions in 8–12 Hz (CP < NP) and 18–30 Hz (CP > NP) • Significant difference in 4–8 Hz (theta) and 12–18 (beta) Hz bands
Lan, Pan, Lian, Huang, and Lin (2014) / China	The impact of thermal changes on sleeping quality using EEG recordings	• Substantial variation in the measured time of slow-wave sleep (SWS) • Substantial decrease in the recorded periods of SWS at 30 °C than at 26 °C or 23 °C • A decline in the subjective sleeping quality at 23 °C or 30 °C in comparison to 26 °C • During the waking state, the participants experienced thermal neutrality at 23 °C, slight warmth at 26 °C and warmth at 30 °C. Whereas, during sleep, the participants experienced uncomfortable cold at 23 °C, slight cold at 26 °C and warmth at 30 °C.

Choi et al. (2015) / S Korea	The impact of IEQ parameters: Temperature, odour irritants and sound on stress levels measured by EEG	• Increased stress levels of the occupants when they were exposed to a temperature[1] of 30 °C
Lv et al. (2017) / China	EEG recordings to investigate the cerebral reactions to local thermal stimulation on local thermal sensation (i.e., the hand)	• Variation in all bands of the recorded EEG signals during and between thermal stimulation periods • The right temporal and parietal regions recorded an increased activation of the delta band in the ambient temperature (32 °C). • Significant increase in theta band activation in all the brain regions under the metal-based stimulation against the water-based stimulation • This finding indicates that the measured neural and physiological reactions are sensitive to the stimuli type throughout the local thermal stimulation on the hand.
X. Shan et al. (2018) / Taiwan	EEG integration with building control system to develop human building interaction at various temperatures.	• The subjects reported an increase in positive emotions during the Neutral thermal conditions (26°C) compared to (23 and 29 °C) conditions. • They have developed a Machine learning-based EEG pattern recognition, see figure 3.5. Based on their EEG recordings of various assigned tasks to the subjects during various thermal conditions.
Aizawa et al. (2019) / Japan	Brain activation by fMRI throughout the entire body thermal stimulation of 47.0 °C, 32.0 °C, and 17.0 °C.	• The recorded local activation in the anterior cingulate cortex, inferior parietal lobe and insula were independent of local and whole-body stimuli. • The frontal brain regions and the caudate nucleus were found to be interrelated to pleasantness, while the anterior cingulate cortex and the medial frontal were found to be related to unpleasantness. • The processing of the perceived thermal pleasantness/unpleasantness and the consequent discriminative and hedonic components were found to be processed by different regions in the brain.
M. Wu et al. (2020) / China	EEG recordings of the brain response to develop a model of thermal comfort detection.	• The developed EEG analysis method could discriminate the thermal feelings of the participants with an accuracy of almost 90%.
(Budiawan, Sakakibara, and Tsuzuki, 2021) / Japan	EEG and Psychomotor Vigilance Task to measure the participant (two different ethnic groups) response to heating and cooling	• Reported EEG variation between two groups of ethnicities. • Lower EEG potential in hot conditions. • The reaction time varied between the two groups in air-conditioned environment, both in heating and cooling.
(Xiaoyue Lang, Pawel Wargocki, and	EEG to measure the cognitive performance in moderate to hot indoor environment.	• EEG relative power has significant correlation to TC and the subjects' cognitive performance.

[1] The impact of the other IEQ parameters is not reported in this paper as they are irrelevant to the scope of this review.

Weiwei Liu, 2022) / China		• The Delta band had negative correlation while all other (theta, alpha and betta) had positive corelation. • The relative power of electrode P7 (at the optic lob) is the most significant to TC and cognitive performance at higher temperature.
(X. Zhang et al., 2022) / China	EEG and salivary secretory immunoglobulin E (S-IgE) test to investigate the thermoregulation mechanism in different indoor environments	• EEG relative power (for alfa and betta bands) was lowest at neutral environment. • S-IgE concentration was highest in neutral environment. • Higher S-IgE concentration is combined with an increase in absolute power in the AF3 electrode for alpha band and the T8 electrode for the theta band. • Higher S-IgE concentration is combined with a reduction in the absolute power in the T8, FC6, F7, and F8 electrodes for the betta band.
(Lan, Tang, Wargocki, Wyon, and Lian, 2022) / Denmark	EEG to measure the cognitive performance at different air temperature	• In hot air temperature (>26 C) the cognitive performance significantly decreased
(Han and Chun, 2021) / S. Korea	EEG recording for thermal discomfort and thermal displeasure	• The relative power for Gamma and Betta bands increased during thermal displeasure by heating, while Theta power decreased. • The overall EEG power increased during both hot and cold thermal discomfort

In this review, six main brain regions reported direct activity variation triggered by thermal stimulation (Table 3.9). Additionally, all the previously mentioned brain waves in Table 3.8 are reported to have direct variation driven by the change in thermal environment.

*12 **Table 3.9:** Reported spatial and functional brain activation variations due to thermal stimulation.*

Spatial/Brain Areas		
Brain area	**Reported variation**	**Number of Reporting studies**
Amygdala	Minor signal magnitude change	2
hypothalamus	Minor signal magnitude change	2
Frontal cortex region	Significant Band change of theta waves	3
temporal lobe	Change of Alpha amplitudes	2
posterior parietal cortex	Change of Alpha amplitudes. Change of signal intensity	3
Cerebral cortex	Change of signal intensity	4
Functional Waves		
Theta	Relative Power variation	4
Alpha	Relative Power and Amplitude variation	6
Delta	Coherence and Power variation	2
Gamma	Relative Power variation	5
Betta	Relative Power variation	4

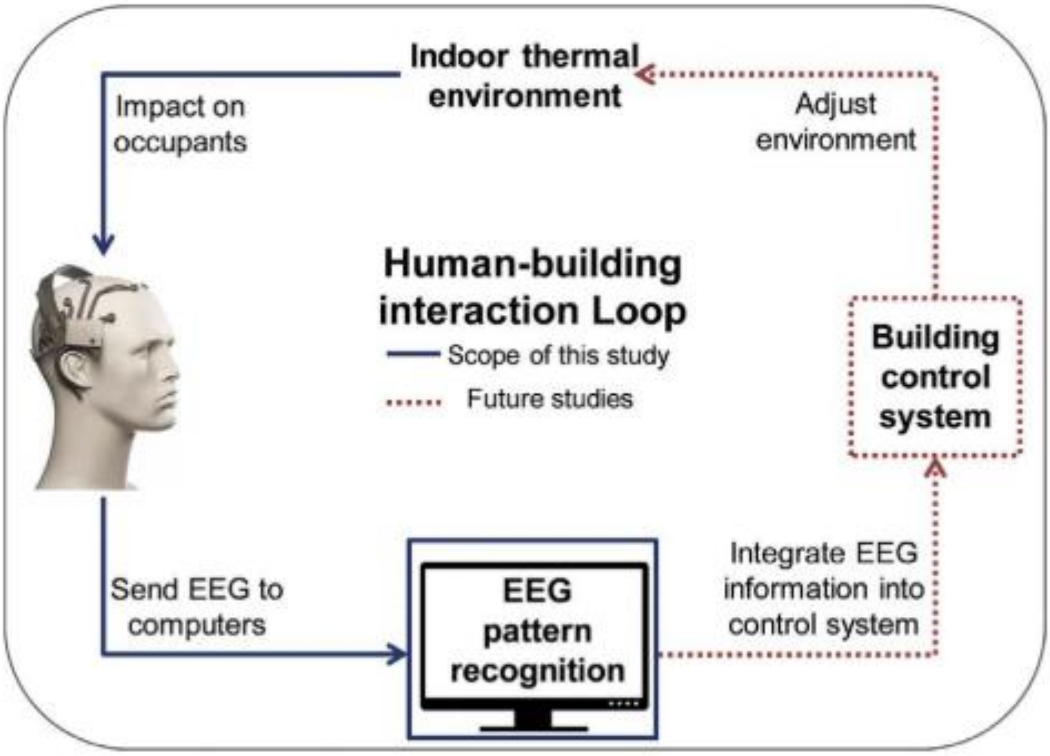
The first reported EEG variation against thermal environment was reported by Chang et al. (2005), who focused on investigating the recorded EEG variations of localised warm versus cold thermal stimulation in humans. The local thermal stimulation was recorded during non-painful warm (40–43 °C) and cold (12–15 °C) against EEG data. Four main changes in EEG patterns were observed:

(1) The cold stimulation caused a decline in the theta band, reflecting higher waking cognitive brain function, which can indicate stress (Alarcão and Fonseca, 2019).
(2) Subsequently, theta and alpha bands recorded a significant increase after the cold stimulation compared to the ambient conditions.
(3) Sequential EEG pattern variations were recorded during and post the thermal stimulations during warm and cold stimuli.
(4) Significant EEG coherence in alpha and delta bands during the thermal stimulations.

These significant findings imply that the same neural channels process the warm and cold stimulations differently, which results in the variation of the EEG patterns. This indicates that the variations in EEG recordings' patterns are encoded relating to thermal stimuli.

In terms of the resulting thermal comfort, Aizawa et al. (2019) showed that various brain areas are associated with thermal satisfaction and dissatisfaction. For instance, the frontal brain regions and the caudate nucleus are related to pleasantness, while the anterior cingulate cortex and the medial frontal are related to unpleasantness. Furthermore, the activation of discriminative and hedonic elements of local stimulus triggered several brain areas, e.g., the insula, the inferior parietal lobes, the medial prefrontal cortex, the middle frontal cortex, the anterior cingulate cortex, the medial prefrontal cortex, and the posterior cingulate cortex. These findings are critical to justify the individual variation of indoor thermal comfort that is barely captured in any building assessment or standard (X. Lang et al., 2022). The reviewed studies presented in Table 3.8 have shown that the human brain is wired to perceive the thermal environment, to some degree, differently. Technology advancements have further allowed researchers to integrate PTC into indoor environment control systems.

In another study, X. Shan et al. (2018) developed an EEG model for enhancing human-building interaction during different indoor thermal conditions to experimentally examine the correlations between EEG recordings against the occupant thermal perceptions during cognitive tasks. Their comprehensive thermal and cognitive parameters analysis was utilised to develop a machine learning-based EEG pattern recognition, as displayed in Figure 3.5. This study showed that absolute thermal comfort is achievable subjectively and tailored to the occupants' thermal perception measured by brain activity. furthermore, this system's complicity remains a challenge that may impede its widespread implementation. The results achieved by X. Shan et al. (2018) may potentially shape the future indoor environment, resulting in customised thermal environments based on the occupant's transient thermal perception.



*15 **Figure 3.5:** EEG-based methods as a feedback mechanism of occupants to improve the human-building interaction, adopted from (X. Shan et al., 2018).*

The mechanism of perceiving thermal comfort can be explained by applying Kilner, Mattout, Henson, and Friston (2005) theoretical model. This justifies that increasing activity in cortical regions leads to increasing fMRI activation and triggers a change in EEG signal from alpha to gamma band. Henceforth, the correlation between the recorded alpha/gamma variation and the functional state of the cortex could be established and related to the external thermal stimuli.

Most of the activations of the cortical areas are combined with an amplitude declination of the EEG fluctuations in the alpha band and with an intensification in the gamma band, according to several other psychophysical and functional brain mapping experiments. It was also reported that a decline in cortical activation is often accompanying an intensification in the alpha amplitude (Edwards, Soltani, Deouell, Berger, and Knight, 2005; Fan et al., 2007; Kahana, 2006; Kelly, Lalor, Reilly, and Foxe, 2006; Laufs et al., 2006; Martınez-Montes, Valdés-Sosa, Miwakeichi, Goldman, and Cohen, 2004; Sauseng et al., 2005; Stancák et al., 2003; Worden, Foxe, Wang, and Simpson, 2000). Therefore, the activation of the cortical area due to the surrounding thermal environment is intertwined with conscious behaviour and higher thought processes.

3.5 Proposed integration of the measured brain waves in ITC assessment

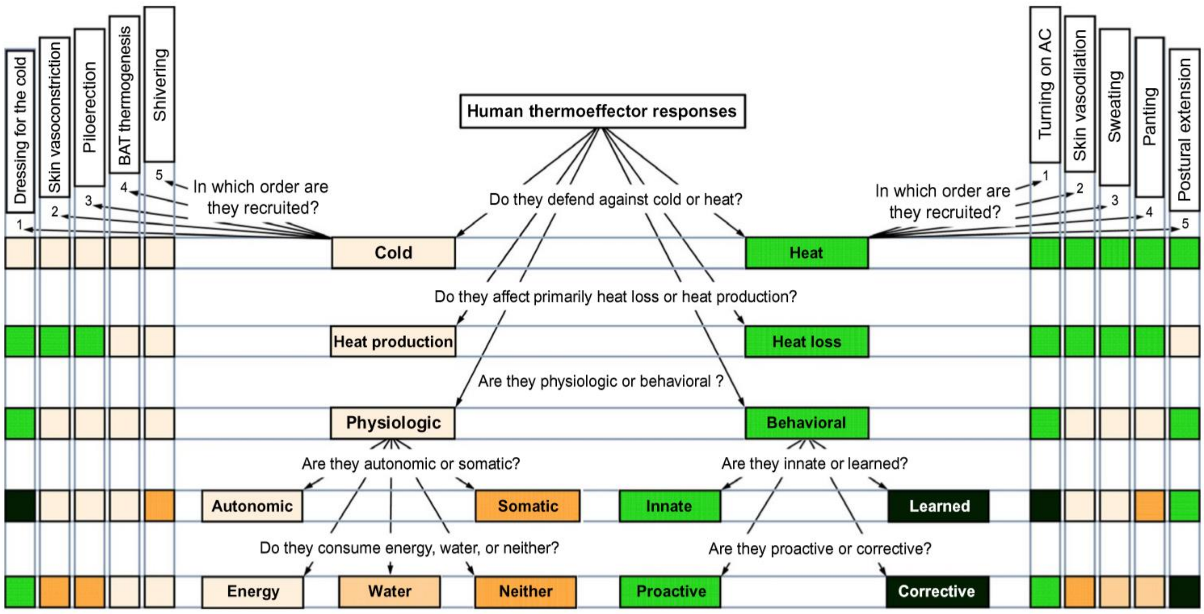
The regulation of body temperature is essential for human survival. This thermal regulation is often achieved via activating various thermo-effector reactions, regulated by our central nervous system. The reported variation in EEG scanning and MRI brain activity mapping (highlighted in Table 3.9), proved the significance of the thermal environments' variation on our brains.

Regardless of its significance in our survival, emotion and behaviour, our understanding of the neural mechanisms of thermal perception are considered incomplete (Bokiniec et al., 2018). Even with a well-established connection, thermal comfort was not analysed based on its influence on mental state, which can be interpreted based on the EEG signals, as discussed in table 3.7. This review demonstrated that many studies have focused on the brain structure and mechanism of processing thermoreceptors neural signals. The reviewed literature did not fully exploit the impact of these neural signals into the greater context of its output in terms of the human experience and the resultant behaviour triggered by thermal perception (Figure 3.6).

Several occupants' behaviour studies have solely focused on energy consumption (Correia da Silva, Leal, and Andersen, 2013; J. Li, Yu, Haghighat, and Zhang, 2019a), as discussed in section 2.2. One of the first identified gaps is the exclusion of the occupant thermal comfort from the current energy ratings, and/or the user's performance in functional buildings, e.g. office buildings, educational buildings, leisure buildings, etc., (Jiang et al., 2021). Even with several regulations governing the IEQ, that support a healthy environment, there is a lack of regulation or guidelines for the long-term effect of ITC on mental health, which significantly impacted by the momentary occupants' state of mind.

This predominant research focus has been reflected in most of the reviewed engineering codes and buildings performance assessments, including green ratings for instance Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), or Green Star New Zealand (Doan et al., 2017; Ncube and Riffat, 2012). ITC is often standardised in all building ratings. The greater context of the actual thermal perception and its impact on the users' state of mind, which contributes to fulfilling the building's predominate function, is rarely considered throughout the building lifecycle and assessments.

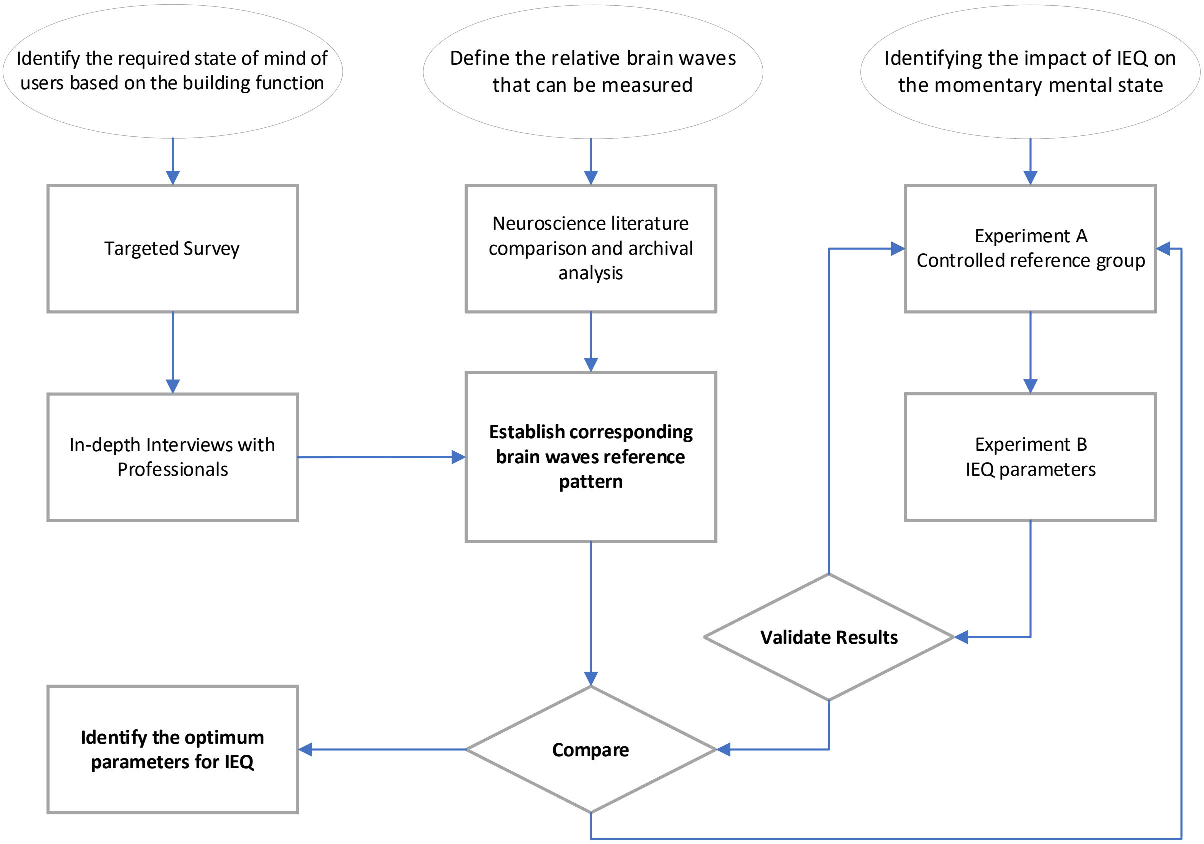
As discussed, in section 3, the PMV model is one of the most popular indices currently used for indoor thermal comfort measurement. However, PMV is incapable to consider the individual thermal comfort perception. For example, Yang et al. (2015) found a deviation of the PMV by overestimating the warm sensation attributable to the prior thermal experience of exposure to a specific regional climate. The fluctuating psychological adjustment may neutralise the occupants' perceived thermal sensation by controlling the skin's thermal sensitivity, consequently causing a hedonic thermal offset of the PMV ratings.



*16 **Figure 3.6:** Human thermo-effector responses, their classification and order of recruitment (Romanovsky, 2018).*

However, several novel methods for emotion recognition using EEG recordings have been reported (Alarcão and Fonseca, 2019; Brouwer, Zander, Van Erp, Korteling, and Bronkhorst, 2015). Applying these methods in thermal comfort studies, with focus on refined range (ambient settings) of thermal alteration, will be a steppingstone for indoor thermal indices. Such studies are critical in future built environments, particularly in shared functional buildings, e.g., schools, museums, public indoor areas, etc. This building functionality is another research gap that should be investigated against the desirable mental state of the users, and how minor changes in the thermal settings may impact it.

Even though the complex interconnectivity between neural receptors and the surrounding environments complicates any empirical research, for instance, certain stimuli, e.g., shapes or colours, could trigger several memories and emotions that vary undetectably where humans are the experiment subject. The complex relationship offsets the empirical measurements of the explicit experience against the measured impact on the brain, directly or indirectly. Consequently, incorporating psychologists and neuroscientists in any empirical study is essential to identify the impact of thermal alteration on the occupants' brains (Azzazy et al., 2020; Coburn et al., 2017), see Figure 3.7.

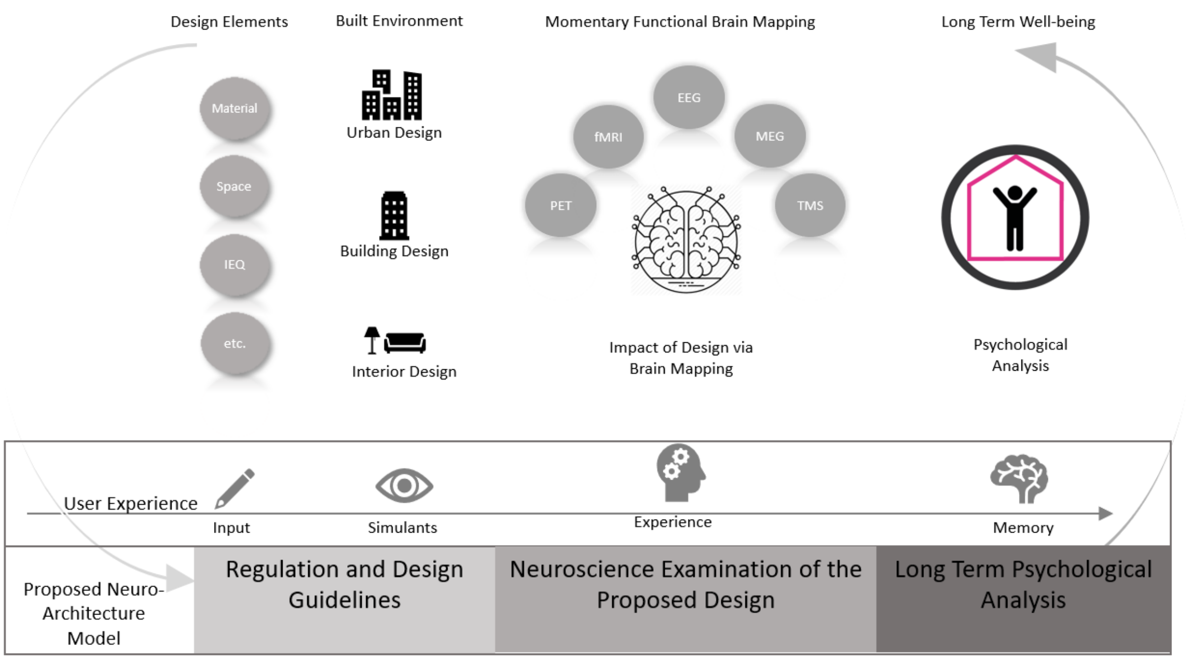


*17 **Figure 3.7:** Proposed framework to include the measured brain waves in ITC assessment.*

This framework depends on the integration of psychologists, neuroscientists, and empirical studies into the building management operation.

The identified challenges of integrating the perceived experience into future designs are possible by the advancement in designing tools. For example, the integration of perceived experience can be achievable by virtual simulation of the building interior variables of IEQ and slightly altering these parameters, namely temperature, smell, colour, sound, or light. The subsequent variation of brain activity can also be identified, creating the ultimate occupant experience. These types of IEQ modelling may create a critical platform, See Figure 3.7, for neuroscientists, psychologists, architects, and urban designers to focus on the occupants' mental health.

The future of the built environment is driven by mental health and well-being. The new emerging research focus and the new scientific branches such as Neuro-Architecture are integrating the momentary experience of the building users into future building codes and regulations (M. Arbib, 2015b; Azzazy et al., 2020). Indoor thermal comfort has a significant advantage for accurate empirical studies over all the other design elements (Figure 3.8). Since any variation of independent thermal variables can be accurately measured and maintained with much higher precision compared to any other design element.



*18 **Figure 3.8:** The different scales of required research to understand the impact of the built environment on the human perception, with proposed procedures to include the user's well-being in the design process (Azzazy et al., 2020).*

3.6 Conclusion

In this review, the development of the indoor thermal indices was qualitatively and quantitatively analysed against the occupant thermal perception. The findings suggest that the individual human thermal perception is not incorporated in the assessment of the overall building performance. Even though the development of PMV includes data for the thermal sensations of many subjects obtained during a comprehensive series of studies, it is considered an extensive field study. Whereas decoding the actual perceived thermal sensation requires a deep understanding of the nervous system from the thermal receptors to the brain.

Subsequently, section 3.2 elaborated the thermal perception process in the central nervous system. Our focus in this paper was further expanded into the experimental studies of indoor thermal perception. It was evident, based on recent reported brain mapping studies, that:

- The controlled variation of the surrounding thermal environments effectuated alterations in the brain activity.
- This variation included six brain areas and all the main five brain wave frequency bands.
- The same neural channels can process the warm and cold stimulations differently, which results in the variation of the EEG patterns.

The primary research gap, discussed in sections 3.4.2 and 3.5, is the elision of these results in the indoor thermal indices.

Our recommended framework introduces a greater context of thermal perception to the future building assessment process. The framework depends on three main streams of evaluation to establish a comprehensive assessment based on the users' actual perceived experience. This holistic view of indoor thermal comfort will improve the future thermal indices and building codes and improve the building thermal performance. The integration of this recommended framework with the current green building ratings in form of scaled point system will improve the overall building performance. Since the distinctive thermal perception of the users' that achieves a satisfactory/targeted state of mind, is essential to any building assessment.

The brain response to thermal variations is evident in six brain areas and all the brain wave frequency bands. However, the current application of indoor thermal comfort indices is far from exploiting this relationship against the users' perception and fulfilling the building function by promoting certain states of mind. Further empirical research exploring the impact of more refined thermal changes, is needed to achieve the desired state of mind that serves the building purpose and improve the users' thermal perception.

Chapter 4 – Survey Study: The perception of Indoor Thermal Comfort: in educational buildings in Auckland, New Zealand

4.1 Prelude

Educational buildings play a vital role in facilitating effective learning environments, offering a wide range of operational functions that distinguish them from other building types. Within these buildings, the occupants' experiences of Indoor Thermal Comfort (ITC) can significantly influence their overall well-being and conditions for student learning. This chapter focuses on investigating the relationship between ITC and occupants' experiences in educational buildings located in Auckland, New Zealand. By conducting a survey-based study, this research aims to quantify the impact of ITC on the occupants' experiences and contribute to the existing knowledge of educational buildings.

The sample size for this study consisted of 109 participants, representing a diverse range of occupants within the educational buildings in Auckland, New Zealand. The collected data was then analysed to derive meaningful insights into the relationship between ITC and the occupants' experiences. The analysis of the survey data revealed several key findings that shed light on the impact of ITC on the occupants' experiences in educational buildings. Firstly, ITC was identified as the most significant factor directly influencing the occupants' mood or mental state, even surpassing cognitive factors. Secondly, the lecture room emerged as a critical space for occupants' thermal perception, suggesting the need for targeted research focus in this area. Lastly, the study found a relatively matching results between the preferred and experienced mental state within the selected AUT campus, indicating a level of alignment between occupants' expectations and actual experiences.

This study significantly contributes to the existing knowledge of educational buildings, and our research by quantifying the impact of ITC on the occupant's experience. By providing insights into the factors that most significantly influence occupants' well-being and performance, this research offers valuable information for improving the design, operation, and management of educational buildings. Additionally, the findings can guide future interventions and strategies aimed at enhancing thermal comfort and optimizing conditions for student learning within educational environments.

In conclusion, this chapter sets the stage for the subsequent sections of the thesis, which will investigate deeper into the methodology, findings, and implications of the study. By examining the relationship between ITC and the occupants' experiences in educational buildings, this research aims to contribute to the broader understanding of how indoor environments impact human well-being and performance in educational settings.

4.2Introduction

The predominant goal of any functional building is to create a suitable micro-environment for the occupants to pursue the intended building function (e.g., work, education, leisure, etc.)(Allen and Macomber, 2020; Chism, 2006). Respectively, buildings deliver the temperature, humidity, lighting, and ventilation necessary for people to live, learn and work effectively (Curwell, Cooper, Deakin, and Symes, 2005; Y. Wu et al., 2022). For educational buildings, the indoor spaces are expected to offer a broader range of different purposes, i.e., learning, collaboration, inspiration, leisure, etc... Conversely, the primary theoretical educational purpose of a building is to contribute to the quality of the educational experience by offering a good relationship between the occupants and their surrounding environment (Anderson and Holloway-Libell, 2014; O'Brien, Lawlor, Chambers, and O'Brien, 2020).

Accordingly, governments are now particularly interested in the evaluations and assessments of educational buildings' performance, seeking to increase the effectiveness of educational programs and to improve economic efficiency (Khalil, Kamaruzzaman, and Baharum, 2016; Rothwell, Hohne, and King, 2018). These assessments have introduced regulations, building codes, and rating systems. However, the new growing academic studies with focus on the human behaviour and health is rarely included in building performance evaluations (Azzazy et al., 2020; Stamper et al., 2016).

The lack of thermal comfort standards in educational facilities is due to the complexity of these surroundings; current regulations such as ISO 7730 (ISO, 2005c), ASHRAE 55 (ASHRAE, 2004), and EN 16798-1 (CEN, 2019) seem to fall short of meeting the needs of students and teachers in terms of thermal comfort and thermal perception. These standards, which do not take into account the preferences of students and teachers, refer to data gathered in laboratories (ISO, 2005c) or field studies using comfort data obtained on healthy adults in buildings around the world (M. Humphreys et al., 2015), Standards are frequently based on dose-response models, which are unable to account for people's unique preferences and demands, as they were often developed for environments like offices and do not take into consideration the peculiarities of educational facilities (Lamberti, Salvadori, Leccese, Fantozzi, and Bluyssen, 2021). Meanwhile, Van Note Chism and Stanley (1999) defined the environment of learning as "Environments or spaces that provide experience, stimulate the senses, encourage the exchange of information, and offer opportunities for rehearsal, feedback, application and transfer are most likely to support learning". These definitions are rarely reflected in any building code, assessment, or rating schemes (Doan et al., 2017; Taleghani et al., 2013; Xue et al., 2019)

Most of the reviewed literature has focused on reducing the total energy demand, building envelope, recovery/reduction of the building's wasted energy, optimisation of utility consumption, etc. (de Wilde, 2019; Jain, Burman, Robertson, Stamp, Shrubsole, Aletta, and Raynham, 2020; Mallory-Hill et al., 2012). Even occupant behaviour studies have focused on energy consumption (Correia da Silva et al., 2013; J. Li et al., 2019b). This predominant focus has been reflected in the current engineering codes and buildings' rating/certification guidelines such as; Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), or Green Star New Zealand (Doan et al., 2017; Ncube and Riffat, 2012). Even with several regulations that promote a healthy environment, i.e. governing the indoor air quality, natural light exposure, etc., there are no national or global regulations or guidelines that focus on the long term effect of the built environment on mental health, or that aims to address impacts on the occupant's state of mind (Azzazy et al., 2020). Since the thermal environment can significantly impact students' well-being, providing thermal comfort in classrooms is crucial to enhance students' productivity and health (Lamberti, Fantozzi, and Salvadori, 2020).

Little research on educational spaces have focused on the design of educational spaces and how it impacts the users' state of mind or conveys a non-verbal message --such as; being hospitable, inspiring, appreciating the input, trusting and supportive– that could be powerful learning tools (Abdelaal, 2019; Gulwadi, Mishchenko, Hallowell, Alves, and Kennedy, 2019). Allen and Macomber (2020) introduced a new concept in educational building design, described as a collaborative journey between the students and the staff. According to McLaughlin and Faulkner (2012), based on interviews and psychological analysis, one of the key identified mental states for the subject students is engagement. The study concluded that higher education quality could be enhanced by providing facilities that allow alternate teaching styles to match the student's learning expectations and consider the technological developments of educational tools. The concept of "smart buildings," on the other hand, is proven by the incorporation of machine learning algorithms with automatic control systems in commercial and residential buildings, with the goals of preserving energy, ensuring security, or enhancing occupant's comfort (Kar et al., 2019).

Several studies have further considered thermal comfort in educational buildings based on natural ventilation and energy savings or bioclimate architecture, e.g. (Costa, Freire, and Kiperstok, 2019; Ge, Wu, Chen, and Wu, 2018; Jing et al., 2019; Lau, Zhang, and Tao, 2019; Sanguinetti, Pritoni, Salmon, Meier, and Morejohn, 2017). Most studies have concluded that thermal comfort is critical for educational buildings. Providing an adequate microclimate environment significantly enhanced the occupants' performance (Astolfi and Pellerey, 2008; Zaki, Damiati, Rijal, Hagishima, and Abd Razak, 2017). However, the primarily identified gap in the literature is the absence of investigating the subjective perception of Indoor Thermal Comfort (ITC) and its impact on the occupants' state of mind, which drives their performance.

From a climate-focused perspective, most of the reviewed literature concerning ITC in educational buildings focused on highly humid or hot tropical climate weather, e.g. (Buonocore, De Vecchi, Scalco, and Lamberts, 2020; Ghaffarianhoseini, Berardi, Ghaffarianhoseini, and Al-Obaidi, 2019; Guevara et al., 2021; Lau et al., 2019; Talukdar, Talukdar, Singh, Baten, and Hossen, 2020; Zaki et al., 2017). Consequently, another fundamental identified gap in the literature is the shortage of studies conducted in countries with climates similar to New Zealand, considered subtropical weather with mild temperatures and moderate rainfall (Sturman and Tapper, 1996). This climate specific limitation of the literature is critical, considering the individual perception of thermal comfort. For example, Yang et al. (2015) discovered a deviation of the Predicted Mean Vote (PMV) caused by overestimating the warm sensation brought on by previous thermal experience from long-term residence in a particular region, which could stimulate psychological adaptation. This fluctuating psychological adjustment could neutralise the occupants' perceived thermal sensation by controlling the skin's thermal sensibility, consequently causing a hedonic thermal offset of the PMV ratings.

The critical shortage of the reviewed studies is the association of thermal perception and the occupant's corresponding mood or state of mind, which is the main objective of this study. Addressing these mentioned gaps, this research aims to quantify the impact of ITC on the occupants' state of mind and the variation between the perceived and preferred state of mind, within a university campus. This subject is crucial for enhancing general and educational building evaluations. The indoor environment quality (IEQ) of educational buildings is considered a subject of great significance. IEQ in educational facilities is essential to attaining a specific state of mind since it impacts users' general behaviours, achievements, and happiness. (Earthman, 1996; M.-T. Wang and Degol, 2016).

4.3 Methodology

ITC is a valuable indicator of overall building performance based on the occupants' comfort, health, and productivity (Kishi and Araki, 2020; M. Wu et al., 2020). In general, there are three main methods to investigate building thermal performance: building performance simulation, objective instrumental measurement, and subjective survey of occupants (Song et al., 2019; J. Wang et al., 2018). The building's occupants are the essential arbiters of the inclusive/perceived building's thermal performance. Hence, the occupant's response to the indoor thermal environment is considered the most critical factor for any thermal perception study (F. Nicol and Roaf, 2005). Accordingly, a subjective survey, combined with articulated objectives, comprises the principal post-occupancy thermal performance evaluation method.

Furthermore, thermal perception surveys are critical to estimate the “actual” response of a large population of subjects from an accurately estimated / relatively small sample (Maas and Hox, 2005). Statistically, there are two types of evaluation of the true response, point estimation (by unique value), or interval estimation. The most considered method in subjective thermal surveys is interval estimation using the probability of Confidence Intervals since it provides more information than point estimation and enables critical statistical analysis for a large sample (Ferguson, 2016).

The key advantage of objective thermal perception surveys is the minimal requirements for measuring the physical characteristics of the environment (i.e., temperature, noise, light, etc.) during the evaluation since the main objective is to evaluate the overall occupant’s perception of the thermal performance of the building. Additionally, ITC survey studies are significantly comprehensive for building performance (F. Nicol and Roaf, 2005; Song et al., 2019).

In this study, the quantitative survey was carried out using an online questionnaire. Besides the demographic data, the questions aim to collect data to answer the following research objectives:

- Identify the most significant spaces in the educational building (by time spent) to optimise the overall thermal performance of the building.
- Quantify the significance of ITC against various factors impacting the experienced mental state in an educational building.
- Compare the preferred vs perceived mental state of the occupants.

This study was conducted at [institution name removed]. The survey was advertised to the targeted population (n=2657) twice over three months to ensure a high return rate. Participants could only take the survey once using the unique link feature. The survey was advertised on the university's digital online learning management system and was voluntary without compensation or promotional advertising.

The survey was published on Qualtrics.com through university-provided access. The total number of questions was 15, including several slide bars and matrices. The first page of the survey was a consent form and an information sheet in accordance with [institution name removed] ethics committee requirements and aligned with the granted ethical approval for the entire study.

This survey focused on the overall thermal perception of the occupants and did not include any building environment monitoring. The focus of this research is perceived thermal comfort. It did not include any momentary questions and was not restricted to a particular room. The participants were not advised to answer the online survey in any location, as the focus of the study is to evaluate the overall impact of the ITC on the occupant’s state of mind (or perceived experience) beyond the momentary limitation of the external thermal stimuli.

The psychological questions for the perceived and preferred mental state were designed based on a rating of 11 different mental states; 5 positives, 5 negatives, and one neutral. This approach was based on the reviewed literature for psychological surveys (Alarcão and Fonseca, 2019; Schwarz, 2007; Varela et al., 2017). The ratings of the 11 mental states will quantify the relative significance of each perceived and preferred mental state and allow the statistical description in terms of thermal comfort.

4.3.1 Sample size

The identified participants of this survey are regular users of the same educational buildings, in general, to quantify the survey objectives across the university's buildings. Hence, the comprehensive sample frame of this study (population – N) is the enrolled students in the School of Engineering, Computer and Mathematical Sciences, a total of 2657 students. The selection of a specific school was to guarantee purposive sampling and ensure homogeneity of the independent variables (i.e., Indoor Thermal Environment) across the results as all the students at the identified school share similar facilities (see Figure 4.3); therefore, all participants were subject to a similar thermal environment (Collins, 2010).

The returned survey response was 109, with a proportion of (4.1%). Additionally, the adopted purposive sampling technique is considered nonrandomised sampling, where primary statistical theories or a defined number of participants are not critical to validate the results since participants' exposure to the study variables is indistinguishable (Etikan, Musa, and Alkassim, 2016). This adopted technique is also referred to as "Homogeneous sampling" and is often used to optimise resources or in conjunction with qualitative analysis to collect accurate and specific insight into the subject (Palinkas et al., 2015) as the purpose of this study.

In our selection methodology of students, we are expected to have a lower variance (Var) since our population is more unified and shares the same common purpose and environment. In purposive sampling settings, the sample size will have a lower impact on the stander error (SE) and the variability of the results. These criteria should yield less than 6% variability (De Vaus, 2013; Fowler Jr, 2013). This selection of participants ensured the returned surveys' precision and quality, which will increase the accuracy of the result, even with a lower population of participants (Anderson and Holloway-Libell, 2014; Nardi, 2018).

Furthermore, the returned ratio of the survey (P=0.041) was used to calculate the confidence intervals for one proportion from a finite population (N) using power analysis for sample size (PASS) software. This routine calculates the sample size necessary to achieve a specified interval width at a stated confidence level for a confidence interval of one proportion estimated from a finite population (Machin, Campbell, Tan, and Tan, 2011), the summary of the input data is in table 4.1,. Accordingly, the returned proportion of the survey has a confidence level (C.L) of 96% with a precision (d) of 0.04.

*13 **Table 4.1**: Summary of the sample simulation*

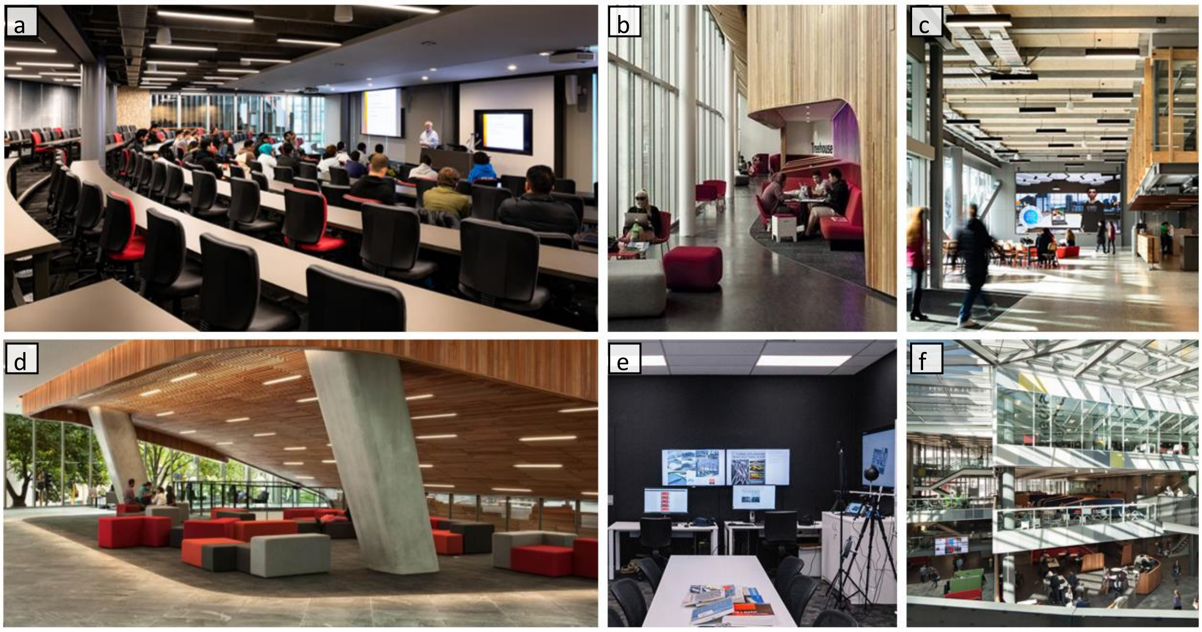
Input	Values
N (Population Size)	2657
P (Sample Proportion)	0.041
d (Precision, Half-Width)	0.020
	0.030
	0.040
Confidence Level C.L (1 - Alpha)	0.900
	0.950
	0.990

4.3.2 Survey design

The research team designed the electronic survey to cover the three research objectives mentioned in section 2. Additionally, the survey was designed to be completed in a short period (less than 10 minutes) to avoid any invalid results due to boredom or fatigue (Groves et al., 2011).

The summary of the survey questions is presented in Table 4.2. The main categories of the questions are demographics, behavioural (i.e., based on time spent) – (C1), psychological (C2) and thermal perception questions – (C3). The thermal comfort questions have been designed based on recommendations of ISO 10551/7730 (ISO, 1995, 2005a). The questions depended on the Likert scale, slider bars, and rating matrices to quantify the survey objective and maintain a practical visual presentation for the participants. The thermal sensation questions were based on the common ASHRAE and ISO 7730 Seven-point thermal sensation scale; Cold, Cool, Slightly Cool, Neutral, Slightly Warm, Warm and Hot (ISO, 2005a; The American Society of Heating, 2004). It should be stated that, in this study, the thermal comfort questions were not momentary. It was generic and used to compare the occupants' overall thermal perception of different spaces with the time spent in those spaces. Accordingly, the participants were not instructed to take the survey in a specific room or building since this study aims to quantify the overall thermal perception of the occupants across the six selected indoor areas, that represent the key activities in any educational building.

The behavioural/time spent questions were percentages based on the total time spent in the university. The ratings included all possible six subcategories of spaces, see Figure 4.2, to quantify the relative significance of each space and match it with the similarly quantified and weighted thermal perception. The time spent analysis is also used as a weighting factor in each subcategory of space specific thermal comfort questions to reflect the level of exposure to each space (Elnabawi and Hamza, 2020; Nikolopoulou and Steemers, 2003). The detailed statistical analyses are in section 3.1. which included four main categories of ANOVA analysis; test of robust homogeneity, nonparametric test of homogeneity based on ranks, symmetry, and normality test.



19 ***Figure 4.2:*** *Different indoor spaces on campus.*

a) Lecture room (Credit to Jason Mann), b) Quiet study rooms (Credit to Simon Devitt), c) Food and drinks outlet (Credit to Jason Mann), and d) Open study area (indoor), e) Laboratory.

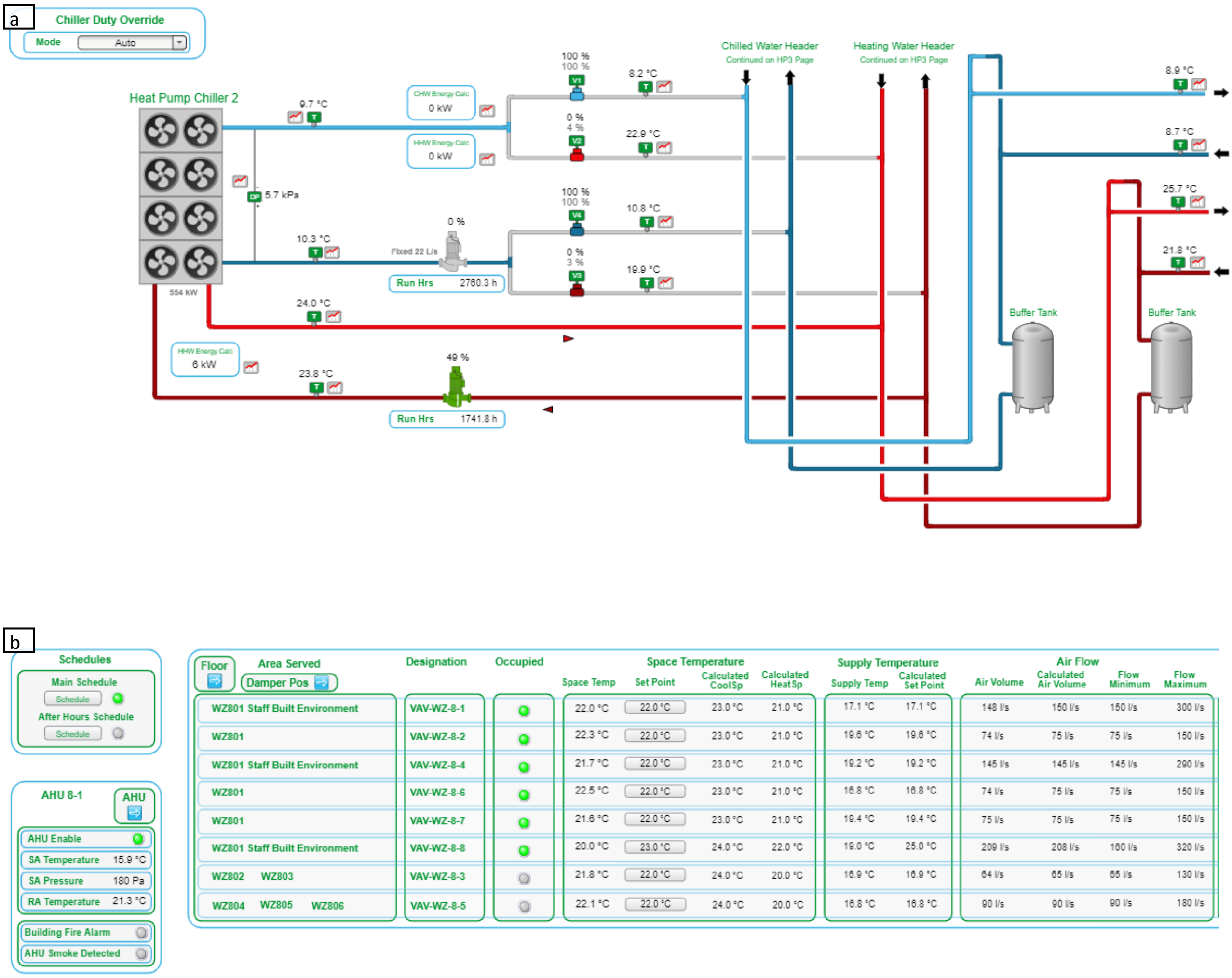
14 ***Table 4.2:*** *Summary of the survey questions excluding the demographic questions by category.*

Main question	Type	sub questions	Category
Overall, what percentage of your time (in campus) do you spend in indoor spaces (inside buildings)? - Time inside [institution name removed] buildings (indoor)	percentage bar		C1
Overall, what percentage of your time (in campus) do you spend in the following spaces	percentage bar	Lecture rooms, Open study areas (indoor), Quiet study rooms, Laboratories, Indoor recreation areas, Food, and drinks outlets (indoor)	
Overall, while inside [institution name removed] buildings, how often do you feel	percentage bar	Relaxed, Focused, Creative, inspired, deep in thought, positively excited, frustrated, disappointed, sad, anxious, angry, bored	C2
How often do you notice your mood (feelings) changing while inside [institution name removed] buildings? - My mood changes	Likert scale		
Which of the following factors impact your mood, select multiple options: (Noise, Thermal sensation (hot or cold), Interaction with colleagues, Interaction with [institution name removed] staff, Study load, Exposure to sunlight, Sad news)	multiple selection		
In your opinion, how do you describe the preferred state of mind in educational buildings. What is your favourite combination? - Relaxed	percentage bar	Relaxed, Focused, Creative, inspired, deep in thought, positively excited, frustrated, disappointed, sad, anxious, angry and bored.	
Overall, how hot, or cold do you often feel, in [institution name removed] Buildings: - I am often.	slider bars for each	Lecture rooms, Open study areas (indoor), Quiet study rooms, Laboratories, Indoor recreation	C3

(Cold, Cool, Slightly Cool, Neutral, Slightly Warm, Warm and Hot)	areas, Food, and drinks outlets (indoor) and in General

In this study, the selection of the indoor spaces limits our research to the occupant's perception of indoor spaces. The analysis of the time spent in indoor spaces is not considered as a behavioural indication of thermal comfort. Since we considered the students to be a passive recipient of thermal environmental conditions within the buildings enclosed envelope (closed ventilation) design in [institution name removed]. This was also disregarded as insufficient supporting evidence in the reviewed literature (De Giuli, Da Pos, and De Carli, 2012).

Another reason to disregard the time spent as an indication of thermal comfort is the configuration of the selected building's (WZ) HVAC system, see Figure 4.3. The HVAC system is considered a swift response central system with available Chilled/Hot water at 8.9 °C /25.7 °C, respectively, at each space which retains the average set temperatures (between 22-23°C) to actual temperatures of 20-22.5°C.

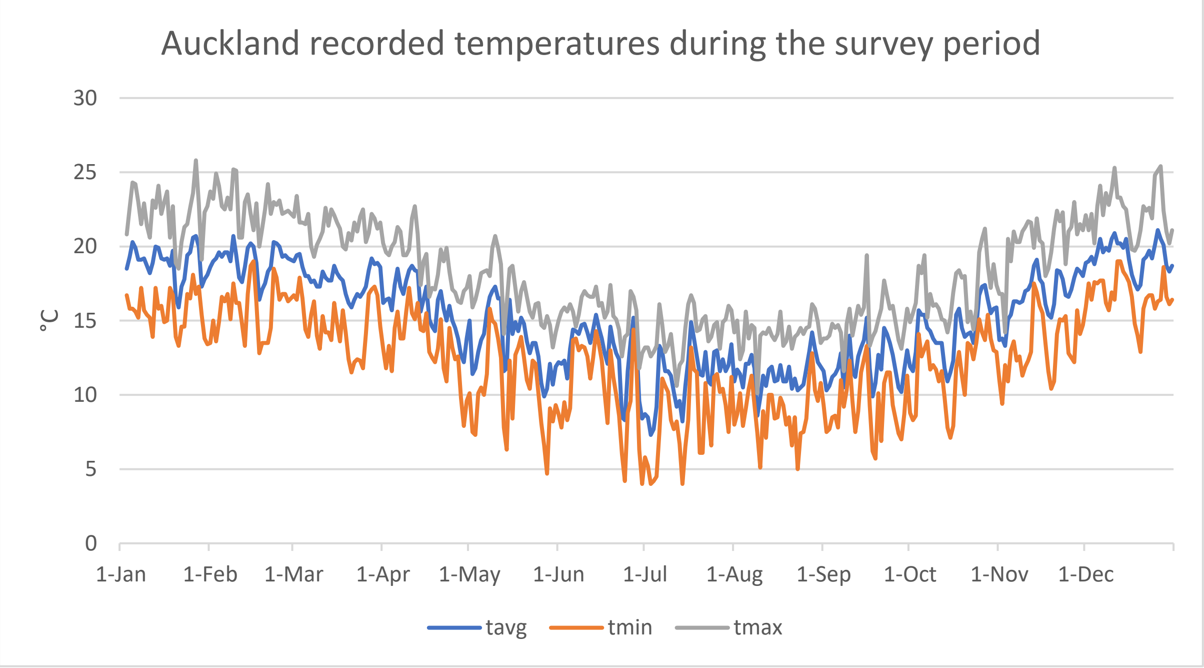


*20 **Figure 4.3:** Process flow diagram of the selected building's (WZ) HVAC system.*

and b) a snapshot of the key operating settings in different spaces, source: [institution name removed] facility management dashboard.

4.4 Results and analysis

The returned results of the survey extended for 5 months. Arguably this extended period would entail various seasonal weather fluctuations. However, as the below temperature graph for the survey period, the entire survey period is considered on the lower spectrum (winter) of the total year temperature fluctuation, see Figure 4.4. Furthermore, as mentioned in the previous section, this study aims to quantify the overall impact of ITC on the occupants' state of mind. This study is limited to the overall perceived thermal association to the experienced state of mind and does not focus on the occupants' momentary thermal sensation.



*21 **Figure 4.4:** Auckland recorded temperature in the year 2020.*

Extracted form (https://www.metservice.com/)

The participants' leading demography percentages were 42% between 20-24 years old, 66% males, and 68% undergraduates, refer to table 4.3a. This demographic distribution reflected the overall demography of the enrolled students, which validated the returned responses with an adequate demographic representation of the overall population.

*15 **Table 4.3a**: Demographic breakdown of the survey response.*

Gender	Count	Percentage

Male	72	66.3%
Female	37	33.7%
Age		
Less than 16	3	02.3%
16 to 19	20	18.6%
20 to 24	46	41.9%
25 to 34	30	27.9%
35 to 44	8	07.0%
45 to 54	3	02.3%
Program		
Undergraduate (Full-time)	74	68.2%
Undergraduate (Part-time)	6	05.9%
Postgraduate (Full-time)	24	22.4%
Postgraduate (Part-time)	4	03.5%

Further cluster analysis was conducted for the demographic description of the returned survey to identify the main leading demographic groups and the statistical significance of each group. Two central clusters were identified; Cluster 1: 69.8% of males between 20 to 24 years enrolled in Undergraduate (Full-time) and Cluster 2 – 65.2% of males between 25-30 years enrolled in Postgraduate (Full-time). The Silhouette Score of the two identified clusters is (0.41) considered in the moderate relativity range due to the limited sample size and the number of variables in the cluster (Fowler Jr, 2013) These two clusters were the most significant, as in Table 4.3b, they reflect similar gender percentages (as the overall gender distribution). The main variation of these two selected clusters is age group. Cluster 1 respondents mostly were aged 20 to 24 and Undergraduate (Full-time), while cluster 2 respondents mostly chose ages 25 to 34 and Postgraduate (Full-time). These two groups also match the overall university distribution for age and study program (postgraduates/undergraduates).

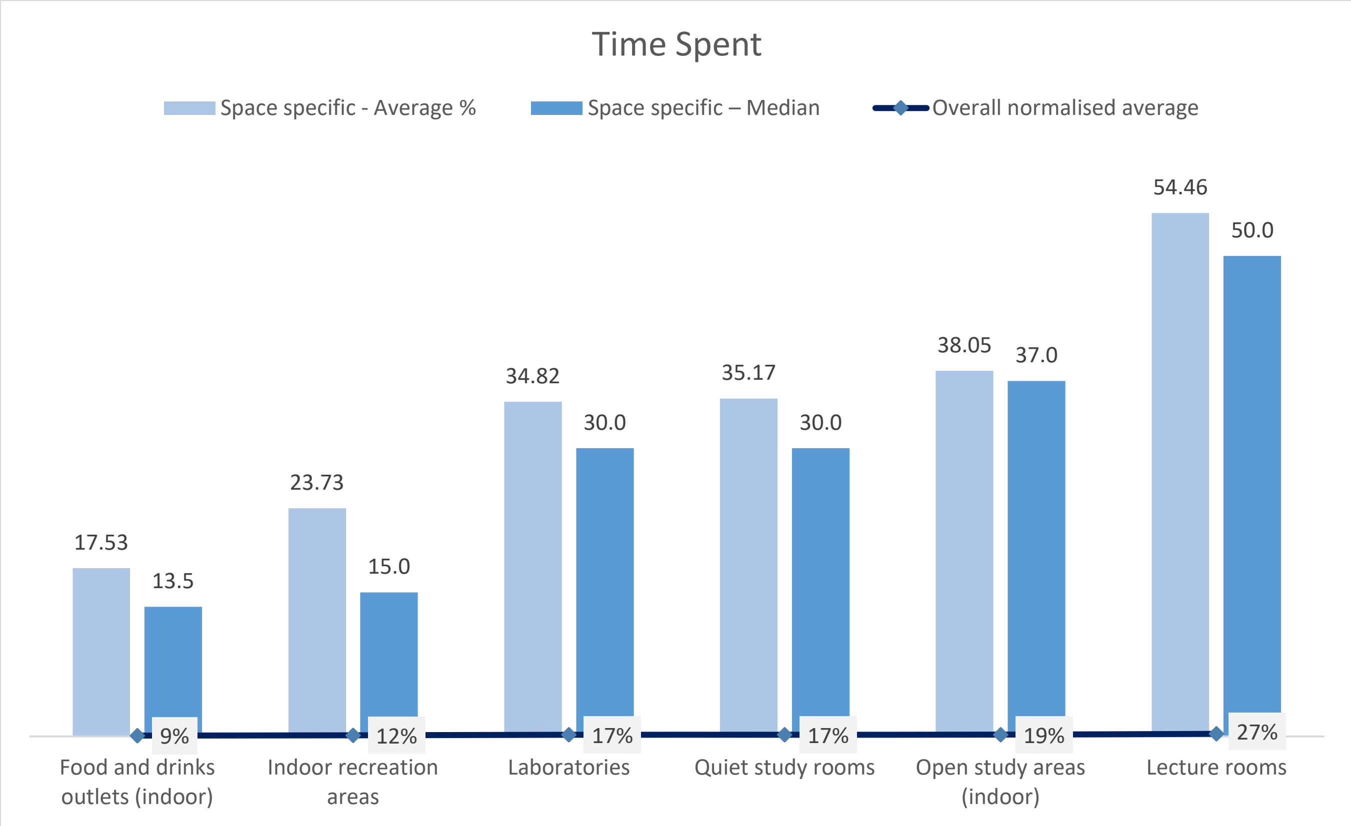
16 ***Table 4.3b:*** *Results of the cluster analysis of the demographic data.*

Category	**Cluster 1***	**Cluster 2****	**Overall**
Less than 16	02.3%	00.0%	01.5%
16 to 19	27.9%	00.0%	18.2%
20 to 24	**69.8%**	00.0%	45.5%
25 to 34	00.0%	**73.9%**	25.8%
35 to 44	00.0%	26.1%	09.1%

Undergraduate (Full-time)	**88.4%**	**26.1%**	**66.7%**
Undergraduate (Part-time)	02.3%	13.0%	06.1%
Postgraduate (Full-time)	09.3%	47.8%	22.7%
Postgraduate (Part-time)	00.0%	13.0%	04.5%
Male	**69.8%**	**65.2%**	**68.2%**
Female	30.2%	34.8%	31.8%

4.4.1 Significant space

To identify the significance of the different spaces on campus, we have used two different time spent questions with percentage sliders. The first question was to quantify the significance of the total indoor time spent. The returned results had an average mean of 78.5% and a median of 85.5%, indicating a significant ratio of the occupant's time is spent indoors. The second question details the percentage of the main six indoor spaces on campus: the results shown in Figure 4.6, rated lecture rooms as the most used. The average percentage of the participants' time spent in the lecture room was 54%. Comparing the lecture rooms to other spaces, weighted to the overall time distribution between all other spaces, it scored the highest percentage of 27% from six different spaces, see Figure 4.5.



*22 **Figure 4.5:** Average percentage (%) of occupants' time spent in different indoor spaces.*

The overall normalised average is scaled against the total time spent in all indoor spaces to reflect the relative significance of each space.

Further ANOVA analysis was conducted to identify the significance of two variables, the percentage of time spent in a lecture room as a response variable and the total indoor time spent, as a factor variable, using the statistics software NCSS. The primary method was the F-test from a one-way (single-factor) analysis of variance. These analyses were only conducted for the lecture room as it was the most selected and have the highest time spent percentage, to validate its significance. The results of the analysis are summarised in Table 4.4.

*17 **Table 4.4:** Summary of the ANOVA analysis of total indoor time vs. lecture room time (null hypothesis)*

Tests of the Equality of Group Variances Assumption

Test Name	Test Value	Prob Level	Reject Equal Variances (α=0.20)	Note
Brown-Forsythe (Data - Medians)	0.8714	0.54645	No	1
Levene (Data - Means)	1.2282	0.30162	No	1
Conover (Ranks of Deviations)	32.8421	0.16673	Yes	2
Bartlett (Likelihood Ratio)	12.6571	0.98682	No	1

Tests of the Normality of Residuals Assumption				
Normality Attributes	**Test Value**	**Prob Level**	**Reject Normality? (α=0.20)**	
Skewness	1.8414	0.06557	Yes	3
Kurtosis	1.0551	0.29137	No	3
Skewness and Kurtosis (Omnibus)	4.5039	0.1052	Yes	3

Analysis of Variance Table and F-Test							
Model Term	**DF**	**Sum of Squares**	**Mean Square**	**F-Ratio**	**Prob Level**	**Reject Equal Means (α=0.05)**	**Power (α=0.05)**
Percentage of indoor time TOTAL	26	15061.24	579.27	0.87	0.635	No	0.616
Adjusted Total	81	51423.61					
Total	82						

Welch's Test of Means Allowing for Unequal Variances					
Model Term	**Numerator DF**	**Denominator DF**	**F-Ratio**	**Prob Level**	**Reject Equal Means? (α=0.05)**
Between Groups	26	53.33	0.30	0.9	No

1: test of robust homogeneity
2: nonparametric test of homogeneity based on ranks
3: symmetry and normality test

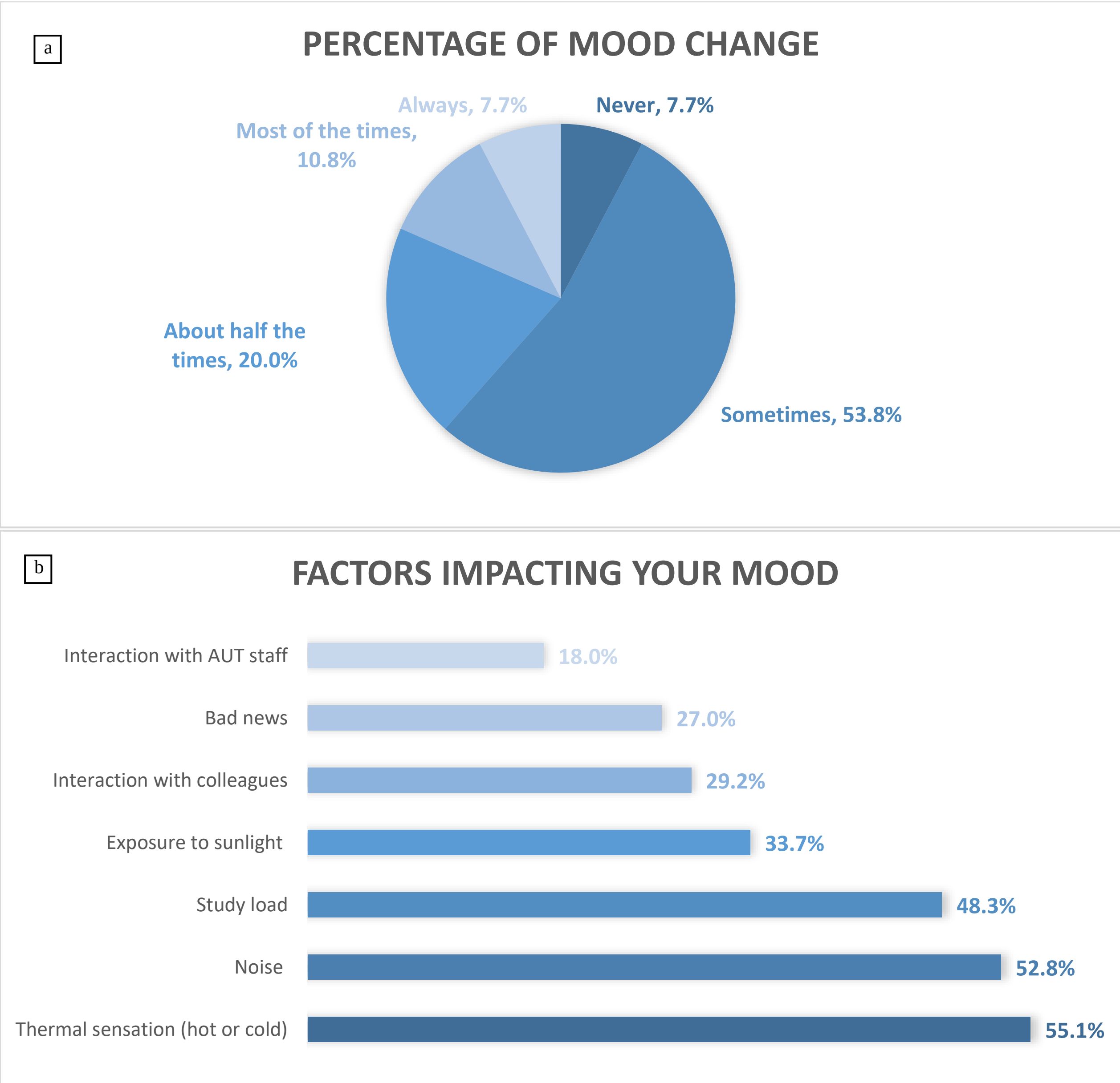
The occupant's response to the time spent in the lecture room was statistically significant compared to all other indoor spaces. All result of Tests of the Equality of Group Variances Assumption indicates that there is no significant difference in variances among the groups. Skewness: The p-value is 0.06557, suggesting a slight departure from normality. The F-ratio is 0.30, with a corresponding p-value of 0.9. This indicates that there is no significant difference in means among the groups, considering unequal variances. Overall, based on the given results, there is no significant difference in means or variances among the groups for the variable.

These findings signify the importance of ITC settings in educational buildings. The currently used ITC indices, such as ISO 7730 (ISO, 2005b) and ASHRAE Standard 55 (The American Society of Heating, 2004), to determine the operating parameter for ITC are based on the rational and adaptive thermal comfort models. However, these standards categorise the indoor spaces in educational buildings based on three categories. The lecture rooms are considered a secondary category (as classrooms). Moreover, several studies have challenged the pertinency of the adopted indices in lecture rooms (Zomorodian et al., 2016).

Our finding in this survey is the identification of lecture rooms as the most critical indoor space in terms of time spent and thermal perception, as further discussed in the following section. This finding is critical to our research to prioritise our stimulation of the ITC efficiently with significant output that improves the overall thermal performance of the building.

4.4.2 The perceived thermal comfort in an educational building

To identify the user's thermal perception, two main questions were asked to scale their awareness of the thermal environment. The first question was a Likert scale, "how often you notice mood changes indoors?" followed by multiple selection questions "What of the following factors impact your mood?". The sequence of these two questions was to indicate the significance of thermal comfort and quantify its relativity. The results are shown in Figure 4.6.



*23 **Figure 4.6:** Summary of the factors and frequency of the occupant mood change.*
a) the frequency of the occupants' mood changes. b) the ranking of the selected factors as drivers for mood change, with thermal sensation selected as the leading factor-in this selection the participants were allowed to select multiple factors.

The key finding was that the students were exceptionally aware of their mood changes (55.1%) due to ITC compared to other key conscious/cognitive factors (i.e., study load 48.3%, interaction with colleagues 29.2%, etc.). There was not any acknowledged study in the literature that compared the thermal perception to other cognitive factors that may impact the occupant's actual, and perceived experience.

These findings, the frequency, and selected factors, highlights the significant influence of indoor thermal conditions on the mental state and performance of students and underscores their acute sensitivity to the connection between thermal comfort and mood. It suggests that students are highly attuned to the fluctuations in their emotional well-being induced by variations in indoor thermal conditions, emphasizing the critical role of thermal comfort in shaping the student experience and performance in educational building.

These findings have important implications for educational institutions and educators, as they underscore the need to prioritize indoor thermal comfort in educational settings. Providing optimal thermal conditions that promote comfort and well-being can have a positive impact on students' emotional experiences, enhancing their overall mood, concentration, and academic performance. By recognizing the significance of indoor thermal comfort and its influence on students' emotional states, educational institutions can create learning environments that prioritize the well-being and success of their students. as the focus of this paper is ITC, further weighted cluster analysis of thermal comfort over all other factors is shown in Table 4.5.

*18 **Table 4.5:** Cluster analysis of the ITC factor against the frequency of mode change.*

	Thermal sensation (hot or cold)		
My mood changes	**Total**	**Blank**	**Selected Thermal sensation**
Never	8.3%	2.0%	13.8%
Sometimes	41.3%	27.5%	53.4%
About half the time	13.8%	9.8%	17.2%
Most of the time	7.3%	5.9%	8.6%
Always	4.6%	3.9%	5.2%
Overall Stat Test of Percentages	**0.724**		
Silhouette score	**0.48**		

Most of the participants who selected "Thermal sensation (hot or cold)" as the most significant factor also indicated that the frequency of their mood change is in the higher spectrum. Additionally, the highest two percentages for the frequency rating "Most of the time" and "Always," 8.6% and 5.2%, respectively, corresponded to participants who also selected "Thermal sensation (hot or cold)" as the most significant factor. This further insinuates the impact of the indoor thermal comfort on the occupant's state of mind. Several reported studies in the literature have indicated a direct relationship between the indoor environment and the occupants' state of mind (Amirbeiki Tafti et al., 2018; O'Brien et al., 2020; Zomorodian et al., 2016).

The actual perceived thermal sensation was collected from two similar sequenced questions. The first was an overall indoor thermal sensation (7 points), and the second was for each indoor space. The significance of the time spent (in section 3.1) was reflected in the thermal sensation in total vs lecture room. The thermal sensation in a lecture room, amongst all other indoor spaces, had the most significant match to the overall indoor thermal sensation, as shown in table 4.6. This further signify the importance of lecture room thermal settings on the overall thermal performance of educational buildings. The basic contingency analysis summary between the two thermal sensations (overall and in each selected space) is below in Table 4.6.

*19 **Table 4.6:** Thermal sensation in selected spaces vs overall thermal sensation*

	Lecture Room						
Overall	**Cold**	**Cool**	**Slightly Cool**	**Neutral**	**Slightly Warm**	**Warm**	**Hot**
Cold	50.0%	36.4%	15.4%	0.0%	0.0%	0.0%	0.0%
Cool	25.0%	45.5%	7.7%	3.6%	11.1%	0.0%	0.0%
Slightly Cool	25.0%	18.2%	46.2%	25.0%	0.0%	22.2%	20.0%
Neutral	0.0%	0.0%	0.0%	53.6%	33.3%	11.1%	0.0%
Slightly Warm	0.0%	0.0%	15.4%	10.7%	55.6%	22.2%	0.0%
Warm	0.0%	0.0%	15.4%	3.6%	0.0%	22.2%	20.0%
Hot	0.0%	0.0%	0.0%	3.6%	0.0%	22.2%	60.0%
Chi-Squared Test			**Basic**		**Advanced**		
Statistical Significance (P-Value)			Very clearly significant		2.38822E-08		
Effect Size (Cramér's V)			Large		0.465749958		
	Open study areas (indoor)						
Overall	**Cold**	**Cool**	**Slightly Cool**	**Neutral**	**Slightly Warm**	**Warm**	**Hot**
Cold	37.5%	33.3%	7.1%	0.0%	0.0%	0.0%	0.0%
Cool	12.5%	44.4%	7.1%	3.7%	7.1%	25.0%	0.0%
Slightly Cool	50.0%	22.2%	35.7%	18.5%	28.6%	0.0%	0.0%
Neutral	0.0%	0.0%	42.9%	44.4%	14.3%	0.0%	0.0%
Slightly Warm	0.0%	0.0%	7.1%	11.1%	42.9%	0.0%	0.0%
Warm	0.0%	0.0%	0.0%	14.8%	7.1%	25.0%	0.0%
Hot	0.0%	0.0%	0.0%	7.4%	0.0%	50.0%	0.0%
Chi-Squared Test			**Basic**		**Advanced**		

Statistical Significance (P-Value)	Very clearly significant	5.66471E-08
Effect Size (Cramér's V)	Large	0.422850009

Quiet study rooms

Overall	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Cold	66.7%	0.0%	8.3%	2.9%	0.0%	0.0%	0.0%
Cool	16.7%	25.0%	50.0%	5.9%	9.1%	0.0%	0.0%
Slightly Cool	16.7%	50.0%	8.3%	41.2%	27.3%	0.0%	0.0%
Neutral	0.0%	25.0%	16.7%	23.5%	27.3%	0.0%	0.0%
Slightly Warm	0.0%	0.0%	8.3%	17.6%	18.2%	50.0%	0.0%
Warm	0.0%	0.0%	8.3%	8.8%	0.0%	25.0%	0.0%
Hot	0.0%	0.0%	0.0%	0.0%	18.2%	25.0%	0.0%

Chi-Squared Test	**Basic**	**Advanced**
Statistical Significance (P-Value)	clearly significant	1.08E-09
Effect Size (Cramér's V)	Large	0.3801769

Laboratories

Overall	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Cold	80.0%	0.0%	9.1%	3.4%	0.0%	25.0%	0.0%
Cool	0.0%	20.0%	9.1%	13.8%	7.7%	0.0%	33.3%
Slightly Cool	20.0%	70.0%	36.4%	27.6%	15.4%	0.0%	0.0%
Neutral	0.0%	0.0%	45.5%	17.2%	23.1%	0.0%	0.0%
Slightly Warm	0.0%	10.0%	0.0%	20.7%	30.8%	25.0%	33.3%
Warm	0.0%	0.0%	0.0%	13.8%	7.7%	25.0%	33.3%
Hot	0.0%	0.0%	0.0%	3.4%	15.4%	25.0%	0.0%

Chi-Squared Test	**Basic**	**Advanced**
Statistical Significance (P-Value)	clearly significant	3.95E-05
Effect Size (Cramér's V)	Large	0.420488

Indoor recreation areas

Overall	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Cold	25.0%	0.0%	0.0%	4.3%	0.0%	50.0%	0.0%
Cool	50.0%	50.0%	0.0%	10.6%	16.7%	0.0%	0.0%

Slightly Cool	25.0%	50.0%	20.0%	25.5%	16.7%	0.0%	0.0%
Neutral	0.0%	0.0%	50.0%	17.0%	50.0%	0.0%	0.0%
Slightly Warm	0.0%	0.0%	20.0%	25.5%	16.7%	25.0%	0.0%
Warm	0.0%	0.0%	10.0%	6.4%	0.0%	25.0%	0.0%
Hot	0.0%	0.0%	0.0%	10.6%	0.0%	0.0%	0.0%
Chi-Squared Test			**Basic**		**Advanced**		
Statistical Significance (P-Value)			clearly significant		0.000686		
Effect Size (Cramér's V)			Large		0.403645		

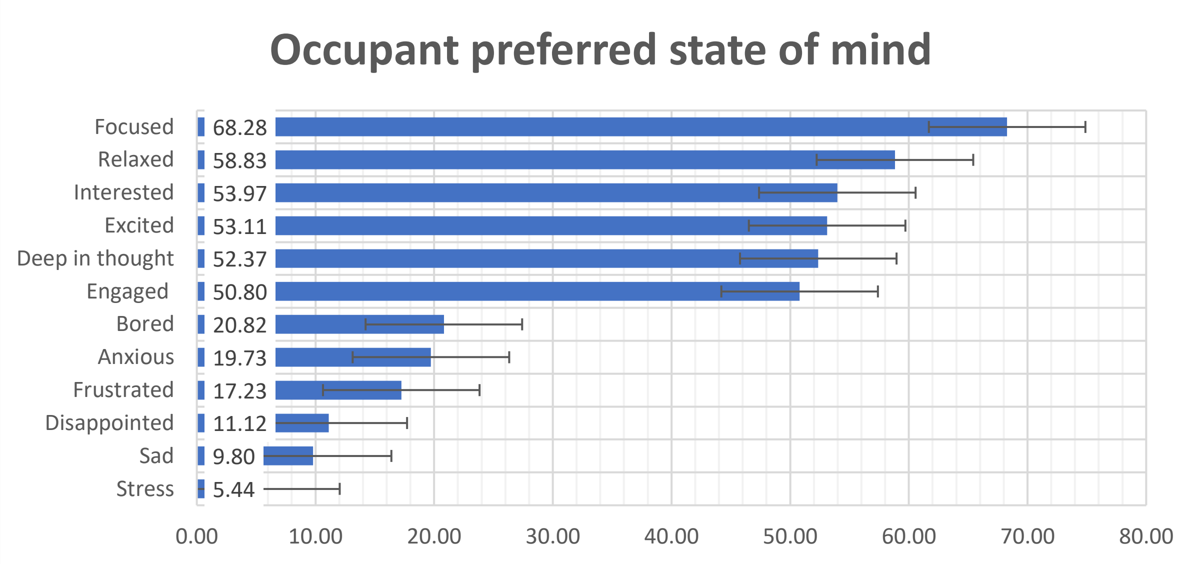
	Food and drinks outlets (indoor)						
Overall	**Cold**	**Cool**	**Slightly Cool**	**Neutral**	**Slightly Warm**	**Warm**	**Hot**
Cold	50.0%	25.0%	0.0%	9.3%	0.0%	0.0%	0.0%
Cool	0.0%	12.5%	22.2%	9.3%	8.3%	0.0%	0.0%
Slightly Cool	50.0%	12.5%	11.1%	25.6%	25.0%	0.0%	0.0%
Neutral	0.0%	25.0%	33.3%	20.9%	41.7%	0.0%	0.0%
Slightly Warm	0.0%	0.0%	33.3%	16.3%	25.0%	50.0%	0.0%
Warm	0.0%	25.0%	0.0%	7.0%	0.0%	50.0%	0.0%
Hot	0.0%	0.0%	0.0%	11.6%	0.0%	0.0%	0.0%
Chi-Squared Test			**Basic**		**Advanced**		
Statistical Significance (P-Value)			Clearly significant		0.110166		
Effect Size (Cramér's V)			Large		0.32196		

This crossmatch also accentuates the importance of the thermal perception of the participants. For instant, all the highlighted values indicate a consistent match between the two thermal perception (overall and space specific). Only the lecture room results matched, in all thermal perception ratings, with the overall thermal perception with high statistical significance of P-Value of (5.66471E-08) indicating a very clear significance. This psychological association between time spent and thermal sensation (matching the time spent ratings) is another indicator of the importance of thermal comfort on the occupant's perception. Consequently, future research and designs should focus on the thermal performance of lecture rooms to optimise the overall thermal performance of educational buildings. As was shown in this study the occupants' thermal perception of lecture rooms is critical to the overall thermal perception of the educational building.

It should be noted that the thermal sensation questions in this section and over the entire paper were not momentary. It was drafted as an overall sensation as our objective is to capture the occupant's awareness of thermal sensation and how it affects their mode.

4.4.2 The preferred mood or state of mind of the occupants

Two different rating methodologies were used to quantify the mental state of the occupants. The first one was the Likert scale to rate eleven perceived mental states as "how often do you feel…." In the second method, the participants were asked to rate the eleven different mental states on percentage slider bars as their preferences "describe your preferred mental state," the results of the preferred state of mind are summarised in Figure 4.7. The leading state of mind was "Focused" 68.28% followed by "Relaxed" 58.83%, the following four states (Interested, Excited, Deep in thought and Engaged) were relatively close (5.80-53.97%).



*24 **Figure 4.7:** Occupant preferred mood or state of mind.*

Rated on the percentage slider bar for their experince in educational buildings.

The results of the six top preferred mental states were clustered and analysed against the perceived mental state. A Likert rating was used to quantify the deviation between the perceived vs preferred mental state, as in Table 4.7. The results indicated that all the significant Confidence Intervals and medians correspond to most of the time or always categories, indicating a strong statistical significance between the perceived and preferred mental states, e.g. the most selected preferred state (Focused) has an average of 75% and median of 89% of participants who selected most of the time they feel focused as the perceived state of mind.

*20 **Table 4.7:** Preferred vs perceived mental state of the top five rated states.*

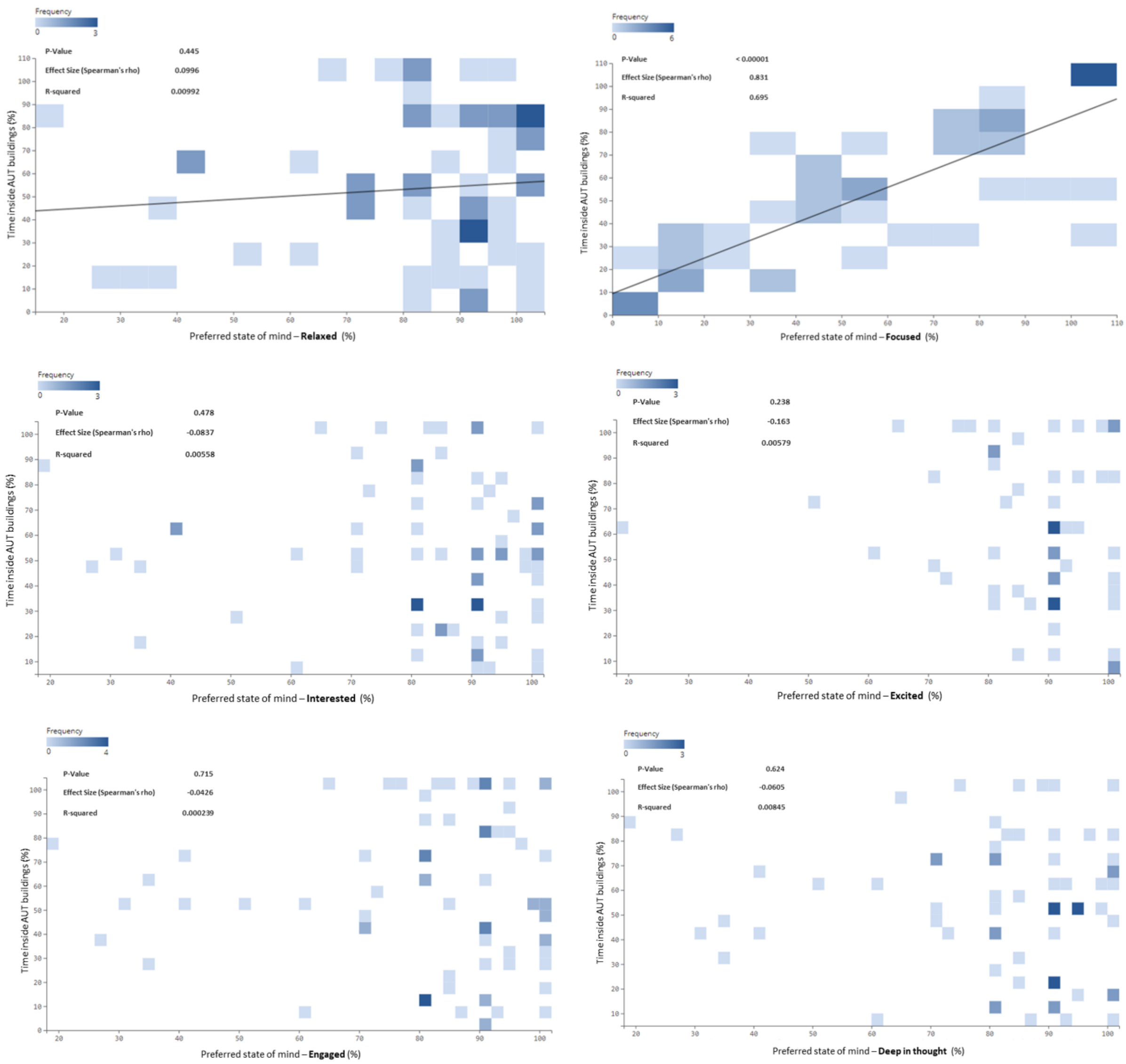
	Preferred state %			
Perceived mental state	**Average**	**Median**	**Confidence Interval of Average**	**Standard Deviation**
Never	41.83	45.0	9.03 to 74.63	31.26

	Sometimes	53.76	50.0	42.42 to 65.11	32.52
Often feel Interested	About half the time	49.73	50.0	34.33 to 65.14	27.82
	Most of the time	**60.80**	**73.0**	41.93 to 79.67	34.07
	Always	**67.75**	**68.5**	8.46 to 127.04	37.26
Often feel Creative	Never	43.75	32.0	4.12 to 83.38	24.90
	Sometimes	47.07	50.0	36.72 to 57.43	26.18
	About half the time	48.10	50.0	35.21 to 60.98	28.30
	Most of the time	**66.12**	**66.0**	51.86 to 80.38	27.74
	Always	42.00	42.0	-4.26 to 88.26	29.07
Often Feel Focused	Never	50.00	50.0	50.00 to 50.00	00.00
	Sometimes	71.00	80.0	53.84 to 88.16	25.55
	About half the time	58.88	57.5	48.62 to 69.13	24.29
	Most of the time	**75.31**	**89.0**	65.78 to 84.85	27.76
	Always	66.83	68.5	33.04 to 100.63	32.20
Often feel relaxed	Never	47.00	47.89	45.67 to 53.28	00.00
	Sometimes	70.29	78.0	53.84 to 88.16	25.23
	About half the time	56.78	56.5	46.22 to 70.17	23.68
	Most of the time	**72.36**	**89.8**	64.76 to 86.88	26.75
	Always	64.32	65.2	32.24 to 98.76	31.10
Often feel excited	Never	18.50	17.5	1.64 to 35.36	10.60
	Sometimes	45.44	43.0	33.93 to 56.95	27.88
	About half the time	58.47	60.0	40.52 to 76.41	32.41
	Most of the time	62.08	60.0	45.16 to 79.01	26.64
	Always	**80.50**	**86.0**	58.51 to 102.49	13.82

The analysis results did not indicate any statistically significant variation between the preferred and the perceived state of mind. However, this is considered a verification of the delivered building function, in general, in terms of all the other indoor design and operational variables. Even though thermal comfort was identified as the most significant factor in section 4.4.2, the wordings of the mood question were specific to the overall perception, and the identified moods are inclusive of all possible indoor stimulants. These results are significant in identifying the building function and purpose from the design to the operation of educational buildings.

The leading state of mind in both questions was ‘Focus.’ This state of mind should be identified as the primary function of the educational building. The survey results in section 4.4.1 (significance of lecture room) further stipulate the importance of this state of mind to the occupants’ experience and preferences for educational buildings. Additionally, identifying the ITC as a significant factor for the occupant's perceived experience should guide future research to efficiently utilise ITC to achieve the principal building function.

Furthermore, the top-rated preferred states of mind were analysed against the overall time spent, and with focus on participants who selected thermal sensation as the leading factor for their state of mind, see Figure 4.8. The results indicated a very strong statistical corelation for “focused” with P-values <0.05. This finding should guid future building designs to target the “focused” state of mind as the predominate building purpose. Moreover, for any post occupancy assessment, the inclusion of a benchmark state of mind is critical to benchmark the building performance.



*25 **Figure 4.8:** Top 6 preferred state of mind against time spend.*
All filtered to participants who selected thermal sensation as a factor that changes their state of mind.

4.5 Discussion

The survey's key finding was the identification of thermal comfort as the main parameter, in comparison to other cognitive parameters, that impacts the occupant’s state of mind. This identification is a novelty in this study, and there was no similar study in the literature comparing ITC to other cognitive factors, most of the reviewed studies concerning the occupant state of mind were behavioural or psychological based (Medlicott, Phillips, Crane, Hinze, and Kuyken, 2021; O'Brien et al., 2020). This identification was evident in section 4.4.2, compared to more cognitive variables such as study load or encountering others.

From a psychological perspective, the human perception evoked by thermal stimulation includes thermal sensation and thermal comfort (Hensel, 1981). Thermal sensation is a subjective response associated with the temperature information of external objects or the environment, evoked by warm and cold receptors in the skin (R. J. de Dear et al., 2013). And thermal comfort is usually considered a combination of subjective sensation and objective environmental interaction (Nakamura et al., 2008). These subjective and objective sensations are often neglected when standardising the thermal sensation and formulating indices (Bluyssen, 2020; Kishi and Araki, 2020; Taleghani et al., 2013). Identifying this thermal sensation as more critical than other cognitive factors signifies the impact of neural pathways and cellular mechanisms of thermal processing, which remain poorly understood (Bokiniec et al., 2018). This signifies the importance of post-occupancy ITC studies, especially with the focus on the fulfilment of the building function, not only from an energy performance perspective but also considering the entire perceived experience of the occupants.

For instance, the Predictive Mean Vote (PMV), the most recent/popular indoor thermal comfort index (Hasan et al., 2016), has the critical disadvantage of not considering the individual perception of thermal comfort. For example, Yang et al. (2015) have found a deviation of the PMV by overestimation of the warm sensation due to the past thermal experience of long-term living in a specific region that could stimulate psychological adaptation. The fluctuating psychological adjustment could neutralise the occupants' perceived thermal sensation by controlling the skin's thermal sensibility, consequently causing a hedonic thermal offset of the PMV ratings. Hence, including more comprehensive thermal sensation parameters in thermal indices is critical to improving the occupant's indoor experience. This rationale regarding the objective and subjective thermal perception should be further exploited to optimise the building function.

The second key finding of this survey was the significant space inside educational buildings, the lecture room. This was reflected in section 4.4.1. with a leading median of 50 and 13% over the second rated space. Furthermore, in section 4.4.2, table 4.5, the only significant match between the overall thermal sensation and the space specific thermal sensation was in the lecture room. Besides emphasising the significance of the lecture room, this cross match also accentuates the importance of thermal perception. This psychological association between time spent and thermal sensation (matching the time spent ratings) is another indicator of the importance of thermal comfort on the occupant's perception.

The findings in this study are critical for future research in educational buildings as they achieve the first two objectives of this research and the identified literature gap. In addition, quantifying the significance of thermal comfort and the key spaces in educational buildings and how the occupants perceive the surrounding thermal environment is critical for future research focusing on the mental state of the occupant in the educational building. This research topic has been subject to significant interest, as highlighted in section 4.2.

The psychological (mental state) findings of this survey, as analysed in section 4.4.3, indicate the preferred mental states of the occupants, see Figure 4.7, to favour the five positive and the one neutral (deep in thought) states. The ANOVA analysis, in Table 4.6, between the preferred and the perceived/experienced mental state did not indicate any significant differences, as all the significant values of the preferred percentages were corresponding to always or most of the time in the experienced states. The critical findings of this analysis are the relative significance of the mood/state of mind "Focus" to be the occupants' most preferred and experienced. The absence of deviation between the experienced states and the preferred states could also signify the ratings of these states and further enforce the leading state of mind to be the most critical in identifying the building function during the lifecycle of the educational building.

Even though the participant's self-reported mood or state of mind may become superficial or impacted by subjective experiences, internal expressions, or external factors (Gunes, Schuller, Pantic, and Cowie, 2011), Independent self-reporting about the participant's state of mind should stipulate important information with limited validity (Bethel, Salomon, Murphy, and Burke, 2007). Since the participants may not describe exactly their actual experienced state of mind, they report what others would answer (Gunes et al., 2011). Therefore, these reported cognitive results will be subject to further function brain mapping experiment to analyse the measured changes due to thermal stimuli, leading to more accurate results (Alarcão and Fonseca, 2019).

Several novel methods for recognising emotions through brain mapping signals have been found in the literature (Alarcão and Fonseca, 2019; Brouwer et al., 2015). Utilising those methods with further detailed thermal comfort studies focused on a more refined range of thermal alteration will yield more productive output that can be a steppingstone for indoor thermal studies based on the actual/measured thermal perception. Such studies are critical in the future built environments, particularly in shared functional buildings, e.g., Schools, Museums, public indoor areas, etc. This functionality of the studied indoor environments reflects another research gap. It should be investigated against the desirable state of mind of the occupants and how minor changes in the thermal settings may impact it.

4.6Conclusion

Indoor thermal sensation is often standardised in building codes and operations. The greater context of the actual thermal perception and its impact on the occupant state of mind, which contributes to fulfilling the building's predominant function, is rarely considered throughout the building lifecycle. In this survey study, it was evident that indoor thermal comfort is a significant factor in the occupants' experience, even when compared to more cognitive factors.

In this study, we aimed to 1) Identify the most significant spaces in the educational building (by time spent) to optimise the overall thermal performance of the building, 2) Quantify the significance of ITC against various factors impacting the experienced mental state in an educational building, and 3) Compare the preferred vs perceived mental state of the occupants. Accordingly, the results of this survey study have:

- Relatively ranked the significance of the indoor functional spaces for the overall thermal performance in the educational building to optimise any future investigations,
- Quantified the impact of ITC on the occupants' state of mind and against several cognitive factors, and
- Identified the occupants' state of mind preferences for educational buildings.

The significance of the lecture room was reflected in both the time spent and by comparing the thermal perception of overall and the space specific thermal perceptions. In this study, the perception association of the occupants between the perceived thermal comfort and the time spent is critical findings. This could efficiently increase the overall performance of the educational buildings; moreover, it signifies the impact of ITC on the overall occupants' experience. These findings guide future research to focus on the simulation of the ITC, e.g., in lecture rooms, to efficiently achieve the desired educational building function.

In this study, there was no significant deviation between the respondents' perceived and preferred state of mind. This finding should only be valid to the limitation of this study in [institution name removed] buildings since the overall perceived state of mind is inclusive of various controlled and uncontrolled stimuli. However, the relativity of the rated states of mind is indicative, beyond the study's limitation, of the objective function of the university building. These top-rated states of mind will be the reference for further brain mapping experiments to quantify the impact of ITC on the measured brain waves. This future research interest would bridge the gap between neuroarchitecture and building performance by measuring the neurological signals in different stimulated indoor environments to achieve the predominant building function.

In conclusion, the future of indoor thermal comfort indices and building performance assessments must include a greater context of thermal perception. This holistic view would result in future indices and comprehensive codes that promote mental health and wellbeing within the educational building. It could even impact the current energy savings and green building ratings when adopting the distinctive thermal perception of the occupants and its consequential state of mind. Furthermore, the building performance should be evaluated based on the building function beyond the energy performance currently dominating the building performance assessments. Thus, further rational, and adaptive thermal studies, focused on the actual thermal perception in lecture rooms, are essential to achieve higher performance and thermal comfortability inside the educational buildings.

The statistical analysis of the survey will be the basis of further in-depth interviews of experts (stakeholders) and users to indicate the overall primary function of educational spaces, adding qualitative analysis to the collected quantitative data in this survey. This mixed method approach will unite the advantages of both quantitative and qualitative research methods; it will provide reliable data with sufficient depth, based on expertise (A. Bryman and Bell, 2007; Onwuegbuzie and Leech, 2005), to identify the predetermined design function of the educational space. This indication will be interpreted into an electroencephalography (EEG) baseline (corresponding brain waves pattern); to be compared to a further experiment. However, the relatively small sample size could be a limitation to establishing such a psychological argument, i.e., the experienced state of mind matches the preferred state of mind. Nevertheless, this statistical significance emphasises the selected state of mind to be the purpose of the educational building.

This study aimed to quantify the significance of thermal perception on the occupants of educational buildings and did not include any environmental monitoring or momentary measurements. This research focuses on the overall perceived thermal comfort within the selected educational building. The participants were not advised to answer the online survey in any location, as the focus of the study is to evaluate the overall impact of the ITC on the occupant's state of mind (or perceived experience) beyond the momentary limitation of the external thermal stimuli.

Chapter 5 – Experiment: The impact of Indoor Thermal Comfort on the occupant performance: in educational buildings in Auckland, New Zealand, measured by EEG.

5.1 Prelude

As established in previous chapters, Indoor thermal comfort is a crucial aspect of the built environment that significantly affects occupant perception and well-being. Achieving optimal indoor thermal comfort involves balancing various factors, including air temperature, humidity, air velocity, and radiant temperature. Providing a thermally comfortable indoor environment is essential to ensure occupant satisfaction, comfort, and the fulfilment of a building's purpose. Recent research studies have indicated that optimal thermal conditions can positively impact cognitive performance, concentration, and learning outcomes in educational and workplace settings. Understanding and effectively managing indoor thermal comfort is critical in the design, operation, and maintenance of buildings. Current engineering practices rely on standards, codes, and indices to achieve acceptable levels of thermal comfort.

Our comprehensive literature review, in chapter 2 and 3, established that the relationship between occupants' perception and the surrounding environment needs to be studied against changes in ITC parameters using advanced measurements and analysis. Recent advancements in neuroimaging and electroencephalography (EEG) methods have allowed researchers to investigate the underlying mechanisms of these changes. EEG offers high temporal resolution and has been used to study neural oscillations and connectivity related to thermal conditions and the state of the mind.

This chapter aims to thoroughly investigate the impact of indoor thermal variation on occupants' state of mind using advanced scientific measurements. With focus on educational buildings and the impact of ITC on occupants' performance to fulfil the building's purpose. The specific objective of this chapter is to Measure the impact of ITC in the identified spaces on occupants' performance and quantify the variation in ITC against occupants' performance.

To address the research objectives, a mixed-method approach is adopted, combining qualitative and quantitative methods. The research methodology consists of several stages, including surveys, interviews, experiments, and data analysis. The methodology aims to integrate user perspectives, expert insights, and empirical measurements to gain a comprehensive understanding of the relationship between ITC and occupants' state of mind.

5.2 Introduction

Indoor thermal comfort is a fundamental aspect of the built environment that significantly impacts occupant perception. It refers to the condition in which individuals feel satisfied with the thermal environment, experiencing neither too hot nor too cold temperatures (Arakawa Martins et al., 2022;

Mansi et al., 2021; Song et al., 2019). Achieving optimal indoor thermal comfort involves balancing various factors, including air temperature, humidity, air velocity, and radiant temperature. However, the human body's ability to maintain thermal equilibrium relies on physiological and behavioural responses, such as sweating, adjusting clothing layers, and seeking thermal sources or shade (Arakawa Martins et al., 2022). The complex interplay between these factors and individual preferences and metabolic rates makes achieving universal thermal comfort challenging. Nonetheless, providing a thermally comfortable indoor environment is essential to ensure occupant satisfaction, comfort, and fulfilling the building’s purpose. Recent research studies have indicated that optimal thermal conditions can positively impact cognitive performance, concentration, and learning outcomes in educational and workplace settings (Allen and Macomber, 2020; Jiang et al., 2021; X. Lang et al., 2022). Serval reported studies, such as (Lamberti et al., 2020; Lamberti et al., 2021; Lau et al., 2019; Zomorodian et al., 2016), have attempted to explore how to optimize indoor thermal comfort in educational spaces, but very few have explored the impacts of Indoor Thermal Comfort (ITC) on users' brain responses and state of mind (Jiang et al., 2021).

In principle, human mind perceives its surrounding built environment via several neurological paths, connecting all senses to the brain. The neural receptors interconnect through the peripheral neural channels and the central nervous system, to effectively integrate all these senses into our perception. This integration impacts all biological and cognitive activities (Azzazy et al., 2020; Bear et al., 2016; Papale et al., 2016). The human central nervous system reacts to stimuli influencing our perception of Indoor Environmental Quality (IEQ), consists of four essential components, namely: Indoor Thermal Comfort (ITC), Indoor Air Quality (IAQ), aural, and visual comfort (Bluyssen et al., 2011; Kishi et al., 2020; Wong et al., 2008). These, four components, include sub-parameters such as temperature, humidity, and air velocity that may directly or indirectly impact the occupants’ satisfaction or sensation of comfort (Goldman, 1999; Guevara et al., 2021; Jiang et al., 2021; Mendell, 2003; WHO, 2015).

As a result, understanding and effectively managing indoor thermal comfort is critical in the design, operation, and maintenance of buildings. The current engineering practices depends on standards, codes, and indices to achieve acceptable levels of thermal comfort. Although these practices are mature and based on very comprehensive subjective evaluations, most of these methods depend on sampling and rarely consider the variation of personal thermal perception over a larger population (Joyce Kim et al., 2018; Z. Wang et al., 2018). Studies developed based on the adaptive thermal comfort theory have pointed out that the perceived thermal comfort varies depending on hedonic and adonic factors (Aizawa et al., 2019; Farrell et al., 2011; M. Humphreys et al., 2015). In addition, the conventional methods are often considered brief observations and are exclusive of the resulting impacts of ITC on the occupants’ perception and performance in functional buildings (Lamberti et al., 2020; Y. Wu et al., 2022). Hence, the relationship between the occupants’ perception and the surrounding environment needs to be studied against changes in the ITC parameters using advanced measurements and analysis.

Underpinning mechanisms of these changes have been investigated using neuroimaging and electroencephalography (EEG) methods (Aizawa et al., 2019; Lv et al., 2017). EEG offers high temporal resolution and provides a useful tool in investigating neural oscillations and connectivity. EEG studies have shown alterations in several frequency bands in response to thermal condition of the environment and state of the mind including attention, emotion, and cognition (Alarcão and Fonseca, 2019; Han and Chun, 2021; X. Shan et al., 2018; M. Wu et al., 2020). For example, alpha (lowest at 21°C and highest at 26°C) and beta (lowest at 26°C and highest at 29°C) band frequencies were reported to fluctuate in response to the subject’s thermal sensation in an ambient thermal environment (Ye Yao et al., 2008).

Few EEG-based studies further explored the impact of thermal pain (Dowman et al., 2008; Shao et al., 2012) and ambient thermal conditions on brain functions (Chang et al., 2005). Several studies also reported similar fluctuation in the EEG power ranges (Chang et al., 2005; Dowman et al., 2008; Lv et al., 2017; M. Wu et al., 2020) and various structural dispersal of the cortical sources (Shao et al., 2012) accompanying the thermal provocations.

These research efforts indicated the direct variation of the neuron's activation and magnitude over various brain regions. Most recent neurophysiological studies demonstrated a neurophysiological correlation to the mechanism of ITC in the peripheral and central nervous systems (cite). However, these findings were limited to the direct neurological activation of external thermal stimulation. Recently, few studies have integrated the measured brain activation into the occupants' perceived experience, e.g. satisfaction, cognitive performance and state of mind (Dong et al., 2022; X. Lang et al., 2022; Y. Wu et al., 2022), identifying ITC parameters as more significant in the subject performance than other indoor environmental quality parameters. Educational buildings are often occupied by large numbers of people with varying levels of thermal sensitivity, making it challenging to maintain optimal thermal conditions.

Recent research progresses in educational spaces have focused on the ways university spaces convey a non-verbal message-such as; hospitable, inspiring, appreciating the input, trusting and supportive– that can be powerful learning tools (McLaughlin and Mills, 2008; Strange and Banning, 2001). Chism (2006) has introduced a new concept in educational building design, based on, student and staff are on a collaborative journey. In this model, when students and tutors are segregated, such as in office configurations, then the collaborative nature of a learning journey cannot happen naturally. According to a study by McLaughlin and Faulkner (2012), based on interviews and psychological analysis of the students, engagement was identified as the main state of mind for the student performance. The study concluded that the quality of higher education can be enhanced by the provision of facilities that allow alternate teaching styles to match the student learning expectations and consider the technological development of educational tools. Several recent studies had further proofed that indoor environment factors, such as thermal comfort, air quality, acoustics and lighting can significantly improve learning outcomes (Castilla, Llinares, Bravo, and Blanca, 2017; St-Jean, Clark, and Jemtrud, 2022; Tampubolon and Kusuma, 2018).

Given the significance of ITC in educational buildings, there is a need for research to investigates the factors that contribute to thermal comfort and the strategies that may be implemented to maintain ideal thermal conditions to enhance occupant performance.

To this end, the current research study aims to quantify the crucial role that ITC plays in educational facilities, to reach a satisfactory state of mind of the occupants', fulfilling the building purpose. With the purpose of developing learning environments that promote academic performance, health, and wellbeing by expanding our understanding of indoor thermal comfort in educational buildings. This research depends on qualitative and quantitative methods to identify the significance of ITC for the occupant's state of mind and the most critical space in educational buildings, that impact the overall thermal performance of educational buildings. The occupant's performance in the identified space is then measured by EEG brain recordings against the controlled variation of ITC.

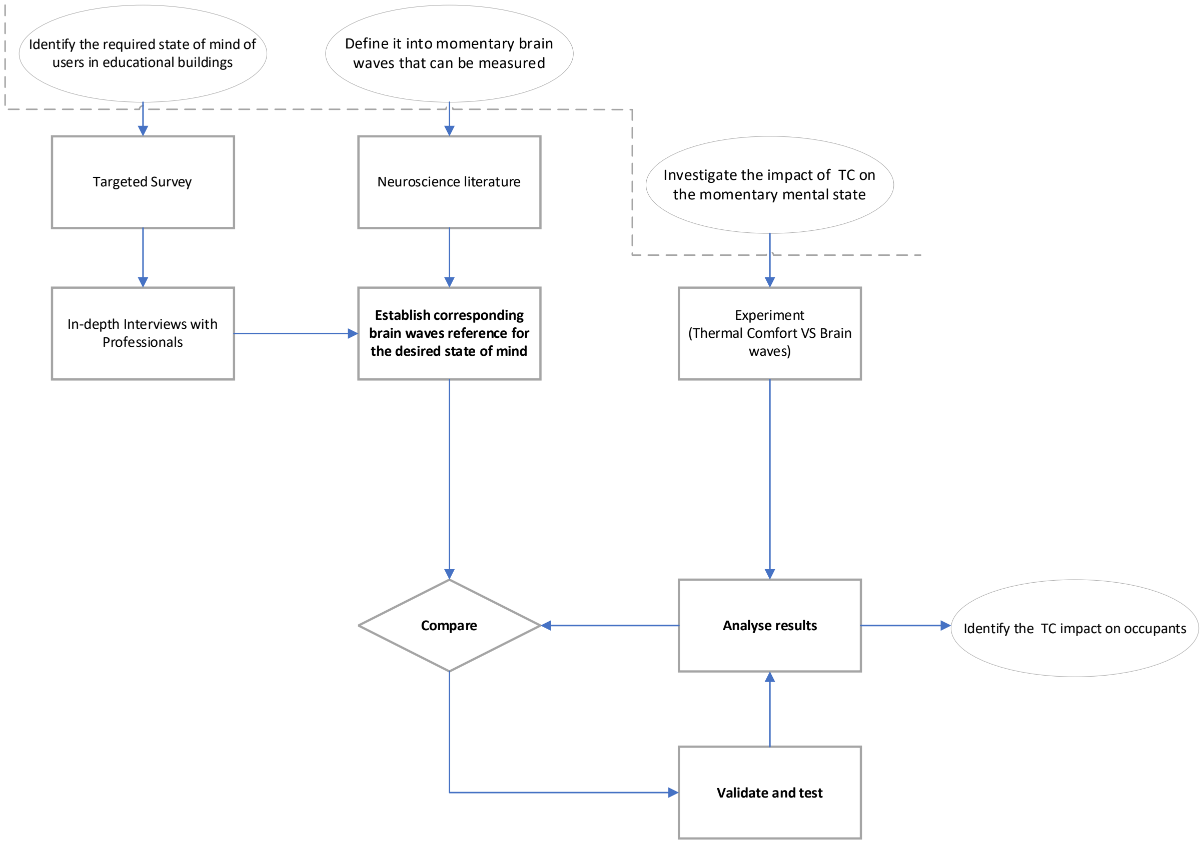
This experiment focus on the momentary experience of the ITC, as a part of the built environment, that can be manifested in the human neural system, more precisely, the brain. The result of the brain mapping recordings, after analysis, will indicate the state of mind of the user which is a measurement of the user mood and can indicate the level of Engagement, Disengagement, Creative Inspiration, Attention, Cognition, Focus, etc against the subject's thermal comfort. This measurement of the impact on the human state of mind, even being temporary, will indicate how the building performing its function and will reflect on the long term of the psychological well-being of users (Poppy L. A. Schoenberg et al., 2018). Since positive brain activities signify physical and mental health beyond negative feelings (Bonnes and Secchiaroli, 1995; Diener and Chan, 2011). Even if it is only transitory, these measurements will reflect how well the building is performing its functions compared to the identified state of mind in section 3.

5.3 Method And Material

The deep engagement between occupants and the built environment complicates any empirical research. Although the complex interconnectivity between neural receptors and the surrounding environments complicates any empirical research, for instance, certain stimuli, e.g., shapes or colors, could trigger several memories and emotions that vary undetectably where humans are the experiment subject. Given the complexity of various interacting networks that underpin behavior, the integration or use of multimodal information in the building setting is critical in identifying and predicting the user's preference (Joyce Kim et al., 2018; J. Li et al., 2019b; Mansi et al., 2021; Y. Wu et al., 2022; S. Zhang et al., 2020; X. Zhang et al., 2022). These studies demonstrate how the integration of multimodal information in the building setting can enhance the identification and prediction of user preferences. By combining data from various sensors and sources, researchers can gain a more holistic understanding of the complex interactions between users, environmental factors, and comfort-related outcomes. This integrated approach enables the development of more personalized and adaptive building systems that cater to the specific needs and preferences of occupants.

The complex relationship, between the external environment and the occupants' perception, could offset the empirical measurements of the explicit experience against the measured impact on the brain, directly or indirectly. Consequently, applying a comprehensive methodology in any empirical study is essential to identify the impact of thermal alteration on the occupants' brains (Azzazy et al., 2020; Coburn et al., 2017).

Therefore, this study depends on user's surveys and experts' in-depth interviews, to identify the most critical space in educational buildings, that impact the overall thermal performance and the occupants preferred state of mind (i.e., engagement, interest, focus etc.), that improve their performance in educational buildings. This mixed method approach is to guarantee that user expectation, and the stakeholder's purpose, of educational buildings are consistent. After identifying the most critical space and preferred mental state in educational buildings, the occupant's performance is measured, using EEG recordings against their thermal comfort (measured by PMV), see Figure 5.1. The subjects of the experiments represent a diversity of all the possible users of the educational buildings and occupied the allocated space, wearing EEG scanner to measure the actual brain function recorded against the controlled change of PMV.



*26 **Figure 5.1:** This study method diagram.*
Provides an overview of our methodology using a combination of experimental, survey, interview, and literature review methodologies. The study focused on the complicated aspects that contribute to indoor thermal comfort by adopting a multimodal approach.

Employing a mixed method approach, as described in Figure 5.1, we aim to investigate the effects of thermal conditions on individual subjects using EEG and behavioral data. The method was applied to address the following research objectives (RO):

1. Identify the significance of ITC for the occupant's state of mind.
2. Identify the most significant spaces and activities in educational buildings.
3. Measure the impact of ITC in the identified space on the occupant's performance.
4. Quantify the variation in the ITC against the occupant's performance.

Our research approach for this study is as follows:

1. Survey: Developing and administering a survey to a sample of participants to gather data on their experiences and perceptions of thermal comfort in indoor environments. The survey includes questions related to demographic information, thermal sensation, and overall comfort level, RO 1 and 2.
2. Interview: Conducting in-depth interviews with experts to gather more detailed information on their experiences and perceptions of thermal comfort. The interviews were semi-structured, allowing for open-ended responses that explored participants' attitudes, beliefs, and experiences, RO 1 and 2.

3. Experiment: Conducting a controlled experiment in which participants are exposed to changing thermal conditions (measured by PMV) while their brain activity is recorded using EEG, RO 3.
4. Analysis: Analysing the data gathered from the survey, interviews, and experiment using statistical techniques and qualitative mathematical methods. The analysis should explore the relationships between subjective experiences of thermal comfort, brain activity, and environmental factors, RO 4.

5.3.1 Qualitative and quantitative data results

The statistical analysis of the survey and the in-depth interviews of both experts (stakeholders) and users is to indicate the overall primary function of educational spaces and the most critical parameters that impact the occupant performance. This mixed method approach will combine the advantages of both quantitative and qualitative research methods; it will provide reliable data with sufficient depth, based on expertise (A. Bryman and Bell, 2007; Onwuegbuzie and Leech, 2005), to identify the predetermined design function of the educational space. This indication will be interpreted into (EEG) baseline (corresponding brain waves pattern); to be compared to the experiment data. As described in Figure 5.1, the study was conducted in three phases: qualitative data collection, section 3.1, quantitative data collection, section 3.2, and experiment phase, section 4.

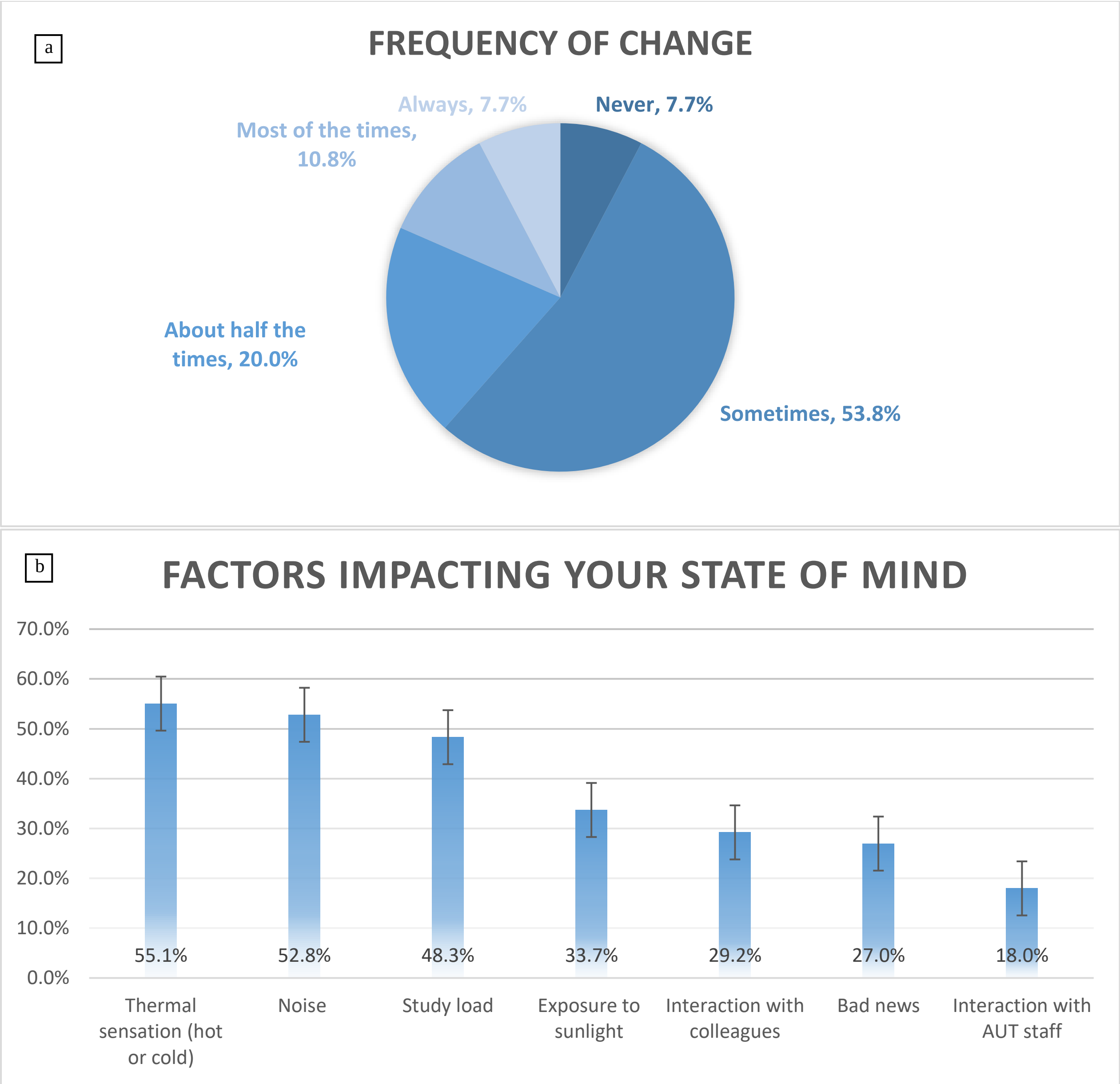
5.3.1.1 Survey results

The previously conducted survey study investigates users' perceptions of the educational facility's thermal comfort levels. The data acquired from educational building users (n = 109) was studied to determine the link between the perceived experience and the purpose of the building.

The quantitative survey in this study was conducted using an online questionnaire. Aside from demographic information, the questions gather information to answer the following study objectives:

1. Determine the most important space in the educational facility (based on time spent and thermal perception) to improve the building's overall thermal performance.
2. Assess the importance of ITC in relation to numerous aspects influencing the experienced mental state in an educational facility.
3. Compare the occupants' desired vs. perceived mental states and find the preferable mental state for the occupants.

The survey's significant conclusion was the identification of thermal comfort as the primary cognitive parameter that influences the occupant's state of mind compared to other cognitive parameters, see Figure 5.2.

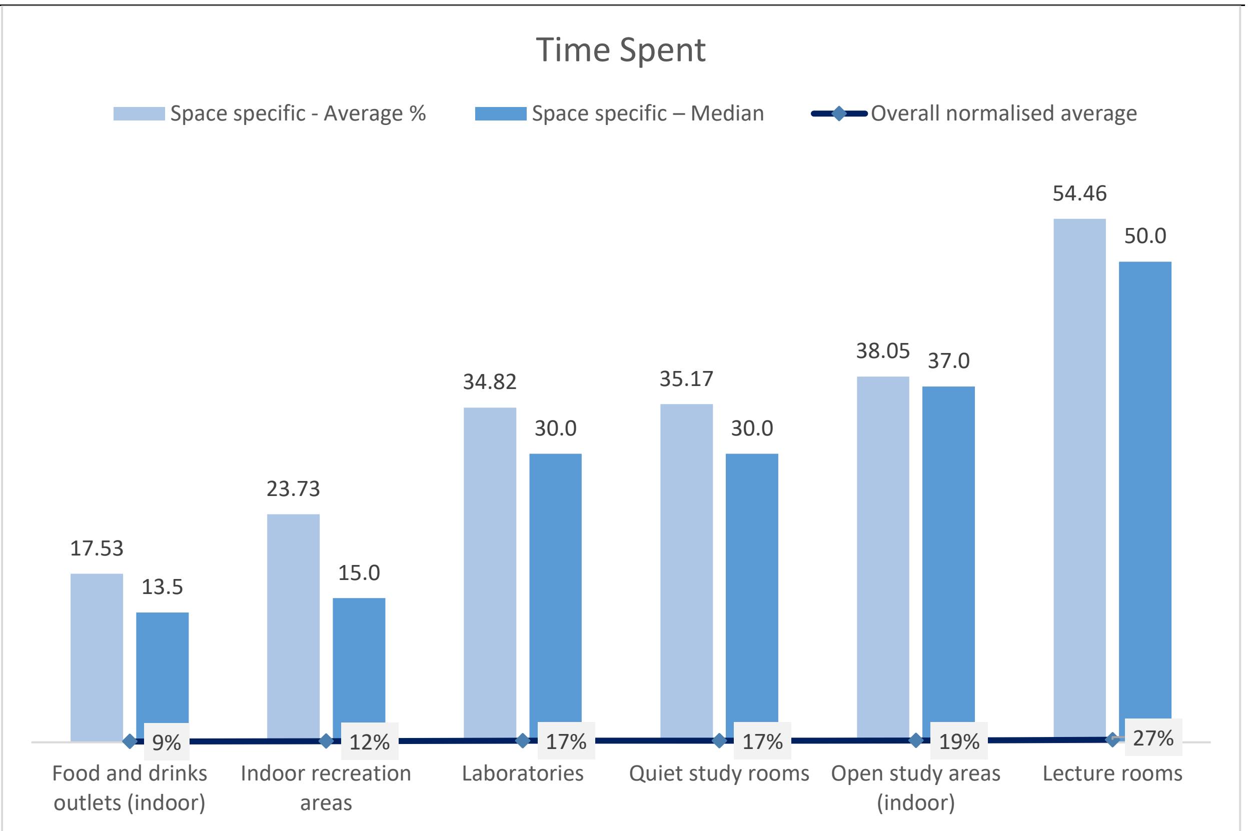


*27 **Figure 5.2:** A summary of the elements influencing occupant mood changes.*
a) the frequency with which the participants state of mid fluctuate. b) the ranking of the identified elements as change drivers, with thermal sensation chosen as the dominating factor.

Another key finding, form the survey stage, is the identification of lecture room significance on the overall thermal performance of the selected building, with a leading median of 50 and a 13% advantage over the second-rated location by time spent, see Figure 5.3. Furthermore, the lecture room had the only substantial match between the overall thermal perception and the space-specific thermal perception, as shown in table 5.1. This crossmatch not only emphasises the relevance of the lecture room, but it also emphasises the occupants' thermal awareness. This psychological relationship between time spent and thermal feeling (which corresponds to time spent ratings) is another indication of the importance of thermal comfort on occupant experience in educational buildings.

*21 **Table 5.1:** Thermal sensation in lecture rooms vs overall thermal sensation*

	Lecture Room						
Overall	**Cold**	**Cool**	**Slightly Cool**	**Neutral**	**Slightly Warm**	**Warm**	**Hot**
Cold	50.0%	36.4%	15.4%	0.0%	0.0%	0.0%	0.0%
Cool	25.0%	45.5%	7.7%	3.6%	11.1%	0.0%	0.0%
Slightly Cool	25.0%	18.2%	46.2%	25.0%	0.0%	22.2%	20.0%
Neutral	0.0%	0.0%	0.0%	53.6%	33.3%	11.1%	0.0%
Slightly Warm	0.0%	0.0%	15.4%	10.7%	55.6%	22.2%	0.0%
Warm	0.0%	0.0%	15.4%	3.6%	0.0%	22.2%	20.0%
Hot	0.0%	0.0%	0.0%	3.6%	0.0%	22.2%	60.0%
Chi-Squared Test			**Basic**		**Advanced**		
Statistical Significance (P-Value)			**Very clearly significant**		2.38822E-08		
Effect Size (Cramér's V)			Large		0.465749958		



*28 **Figure 5.3:** Average percentage (%) of occupants' time spent in different indoor spaces.*
The overall normalised average is scaled against the total time spent in all indoor spaces to reflect the relative significance of each space.

The analytical findings, for the state of mind preference from the survey, revealed no statistically significant difference between the preferred and perceived states of mind. However, these findings are crucial, for the proceeding experimental stage, in determining the function and purpose of educational buildings from design through operation, as shown in Figure 5.4.

*29 **Figure 5.4:** Occupant preferred mood or state of mind, rated on the percentage slider bar.*

The outcomes of the six most desirable mental states were grouped and compared to the perceived mental state. As shown in Table 5.2, a Likert scale was used to evaluate the difference between the perceived and preferred mental states. According to the findings, all the significant confidence intervals and medians correspond to most of the time or always categories, demonstrating a considerable statistical relevance between the perceived and desired mental states.

*22 **Table 5.2:** Preferred vs perceived mental state of the top six rated states.*

		Preferred state %			
Perceived mental state		**Average**	**Median**	**Confidence Interval of Average**	**Standard Deviation**
Often feel inspired	Never	41.83	45.0	9.03 to 74.63	31.26
	Sometimes	53.76	50.0	42.42 to 65.11	32.52
	About half the time	49.73	50.0	34.33 to 65.14	27.82
	Most of the time	60.80	73.0	41.93 to 79.67	34.07
	Always	67.75	68.5	8.46 to 127.04	37.26

Often feel Creative	Never	43.75	32.0	4.12 to 83.38	24.90
	Sometimes	47.07	50.0	36.72 to 57.43	26.18
	About half the time	48.10	50.0	35.21 to 60.98	28.30
	Most of the time	66.12	66.0	51.86 to 80.38	27.74
	Always	42.00	42.0	-4.26 to 88.26	29.07
Often Feel Focused	Never	50.00	50.0	50.00 to 50.00	00.00
	Sometimes	71.00	80.0	53.84 to 88.16	25.55
	About half the time	58.88	57.5	48.62 to 69.13	24.29
	Most of the time	**75.31**	**89.0**	65.78 to 84.85	27.76
	Always	**66.83**	**68.5**	33.04 to 100.63	32.20
Often feel relaxed	Never	47.00	47.89	45.67 to 53.28	00.00
	Sometimes	70.29	78.0	53.84 to 88.16	25.23
	About half the time	56.78	56.5	46.22 to 70.17	23.68
	Most of the time	**72.36**	**89.8**	64.76 to 86.88	26.75
	Always	**64.32**	**65.2**	32.24 to 98.76	31.10
Often feel Positively excited	Never	18.50	17.5	1.64 to 35.36	10.60
	Sometimes	45.44	43.0	33.93 to 56.95	27.88
	About half the time	58.47	60.0	40.52 to 76.41	32.41
	Most of the time	62.08	60.0	45.16 to 79.01	26.64
	Always	80.50	86.0	58.51 to 102.49	13.82

In this survey, the dominant state of mind was "focus." This mental state should be regarded as the fundamental function of the educational building. The survey results (importance of lecture rooms) emphasise the significance of this state of mind to the inhabitants' experience and preferences for educational buildings. Furthermore, establishing ITC as a key role in occupant perception should direct future studies to optimally use ITC to meet the primary building function.

In this study, we aimed to 1) identify the most significant spaces in the educational building (based on time spent and thermal perception) in order to optimise the overall thermal performance of the building, 2) quantify the importance of ITC in relation to various factors influencing the experienced mental state in an educational building, and 3) compare the preferred vs. perceived mental state of the occupants and identify the preferred state of mind of the occupants. As a result, the findings of this survey research have:

- Relatively ranking the significance of the indoor functional spaces in the educational building to optimize any future investigations and identified lecture room as the most critical to the overall thermal performance.

- Quantified the impact of ITC on the occupants' state of mind and against several cognitive factors, and
- Identified the occupants' state-of-mind preferences for educational buildings, which will be compared to the subject performance in the experimental phase.

5.3.1.2 Interview results

The statistical analysis of the survey is the base of further in-depth interviews of both experts (stakeholders) and users to indicate the overall main function of educational spaces and validate the survey results. The in-depth interview has shown a higher level of details and more ability to identify individual thoughts. Based on the viewed literature, especially comparing the focus group and in-depth interview (Almalki, 2016; Anderson and Holloway-Libell, 2014; Guest, Namey, Taylor, Eley, and McKenna, 2017; Olson, 2016), it was identified that in-depth interviews will be more adequate to our research. This qualitative methodology, in-depth interviews, will enable us to identify the stakeholder's and professionals' actual purpose of educational buildings to validate the survey results. Hence it is integrated with the quantitative analysis of the user's surveys, to establish a brain wave reference which can be compared with the user's recordings in the experimental stage.

There are many aspects that effect the sample size for qualitative research, e.g., the study purpose, research design, characteristics of the study population, analytic approach, and available resources (Alan Bryman, 2016; Hennink, Kaiser, and Marconi, 2016). The most common method, found in the literature, for assessing sample size, in purposive sampling, is saturation (Alan Bryman, 2016; Morse, 1995; Nardi, 2018; Olson, 2016). Morse (2015) stated that "Saturation is the most frequently touted guarantee of qualitative rigor offered by authors to reviewers and readers."

In it is the first definition, saturation, in qualitative data collection, refers to the point where no additional issues or insights develop from all the data and all relevant theoretical categories have been recognized, explored, and exhausted (Glaser and Strauss, 1967; Hennink et al., 2016). In this study, saturation will be identified as, reaching the point of describing, the primary purpose, and all sub-categories of the same purpose with its relative significant, of higher educational buildings.

The targeted participants in this interview stage are chosen to represent all the stakeholders engaged in the development and operation of a tertiary educational building. Following the survey, 14 experts were interviewed. All the participants had positions above senior management, such as directors, operations managers, and senior lecturers.

The main objective of the interview is to:

1. Verify the quantitative survey's results and collect qualitative data.
2. Identify the impact of the indoor environment on the user's state of mind.
3. Discuss the performance of building functions (as well as the mental state of the occupants).

The primary analysis of the conducted interview is as following.

Survey Feedback

The main features of the response are as following:

1. All participants agreed that the lecture room is the most important for thermal perception since the occupants spend the most time in it (on a continuous basis). Furthermore, three participants stated that it is one of those settings in which individuals have little control over their thermal

experience, i.e., the inhabitants cannot leave or modify the thermal setting. In such spaces, thermal adaptation is confined to clothes (e.g., wearing or removing a jacket). This further emphasises the importance of lecture room thermal performance.

2. All participants were surprised (or shocked to some degree) when presented with the results of the cognitive impact of ITC, as highlighted in Figure 5.2. Their main justification for the reaction is that, compared to a very cognitive task, the occupants still selected thermal sensation. However, two participants, out of the 14, have further attributed that to poor thermal settings within the building or that occupants are always uncomfortable.

The function of educational buildings in terms of the user's state of mind

In the open discussions in the interview phase, engagement and attentiveness were the main qualities (mental states) that were highlighted. However, everyone agrees that these mental state factors are never highlighted or conveyed to the mechanical design team during the mechanical design process, which results in the thermal performance of the building. Everyone agreed that any consideration, if any, is limited to the architects. Furthermore, everyone agreed that all mechanical design is based on the stated design codes (in any contract) and just the following variables: number of probable occupants and kind of space (activity-based). Three participants have even said that the age of the inhabitants is frequently overlooked.

integration of building function (as mental state of the occupants) into building ratings

All participants agreed that present building assessments (particularly in New Zealand) are confined to the building's energy performance. And found a gap that must be filled. Two participants stated that such assessments will be more advantageous and simpler to execute in office buildings because occupant satisfaction will result in improved performance and higher returns to stakeholders.

Instead of PMV, one expert suggested using the satisfaction scale and adaptive theory. Because PMV works in the laboratory, the same approach will not operate in office buildings owing to the diversity of residents. Were, two participants said that the CIBES has begun a better strategy for the building life cycle called the "soft landing framework," which can include occupants early in the design process. This structure, however, has yet to be adopted in New Zealand.

Significant Quotes to select from in the paper:

"In the middle of a lecture, it is quite hard to get up and put your coat on. It's a very different psychological environment to be in when you're in control of it, and that's sort of the flip side."

"People just don't realise they think they're telling you something about the air when they're not. They're telling you something about themselves and their ability to function in that space."

"People don't have much perception of personal control over that environment. So, they're spending a lot of time in there, and they're almost at the mercy of the building services systems."

"They're putting caps on embodied energy and caps on operational energy, and then over the years the caps will reduce so that we're giving out less and less carbon."

"If you can get the occupiers that the end occupies and the facilities people of the building working with the design team right at the beginning, then the handover process is softer, so they land softly into their new building with some knowledge of what it's going to be and having driven some of the design needs for the building, and then for up to three years after handover, there are study post occupancy valuations, walk rounds, and swapping back of the information so that that knowledge of that building goes back to the designers for their next design."

"If post-occupancy evaluation was to include questions of the occupants about how they're feeling in that environment, is that going to help drive people to build better buildings for that purpose? That would be great."

"I'm seeing more of that, and that in theory will mean that what the client needs of the building will be a building in which I could learn, a building in which I can work, and a building in which I can heal."

"There is already a reasonable amount of work being done on post-occupancy evaluation, including people's views of things. But hardly get looped back to the design stage."

On using different design purposes for different spaces within the building: *"I agree, this is the top for what you want to be looking at. Will Get more of an environment in lecture rooms that fits with the PMV Fagner type theory, and more of an adaptive theory might fit your open and quiet study spaces."*

Summary of key insights gathered from expert interviews and discussions

- Interpreting Feedback Beyond Physical Environment: Occupants often communicate personal preferences and comfort levels that extend beyond the physical environment. Feedback provided is more about themselves and their comfort than objective observations of the space.

- Limited Perception of Control: Occupants frequently perceive limited control over their environment, especially regarding building systems. This perceived dependence on building services can affect their overall satisfaction.

- Emphasis on Energy Conservation: The interviews stressed the significance of energy conservation in building design. The concept involves setting limits on embodied and operational energy use, with the aim of reducing carbon emissions progressively.

- Collaborative Design Approach: Collaborative efforts involving occupants, facilities personnel, and the design team from project initiation were highlighted as essential. Such collaboration ensures smoother transitions and better-informed designs, ultimately benefiting the end users.

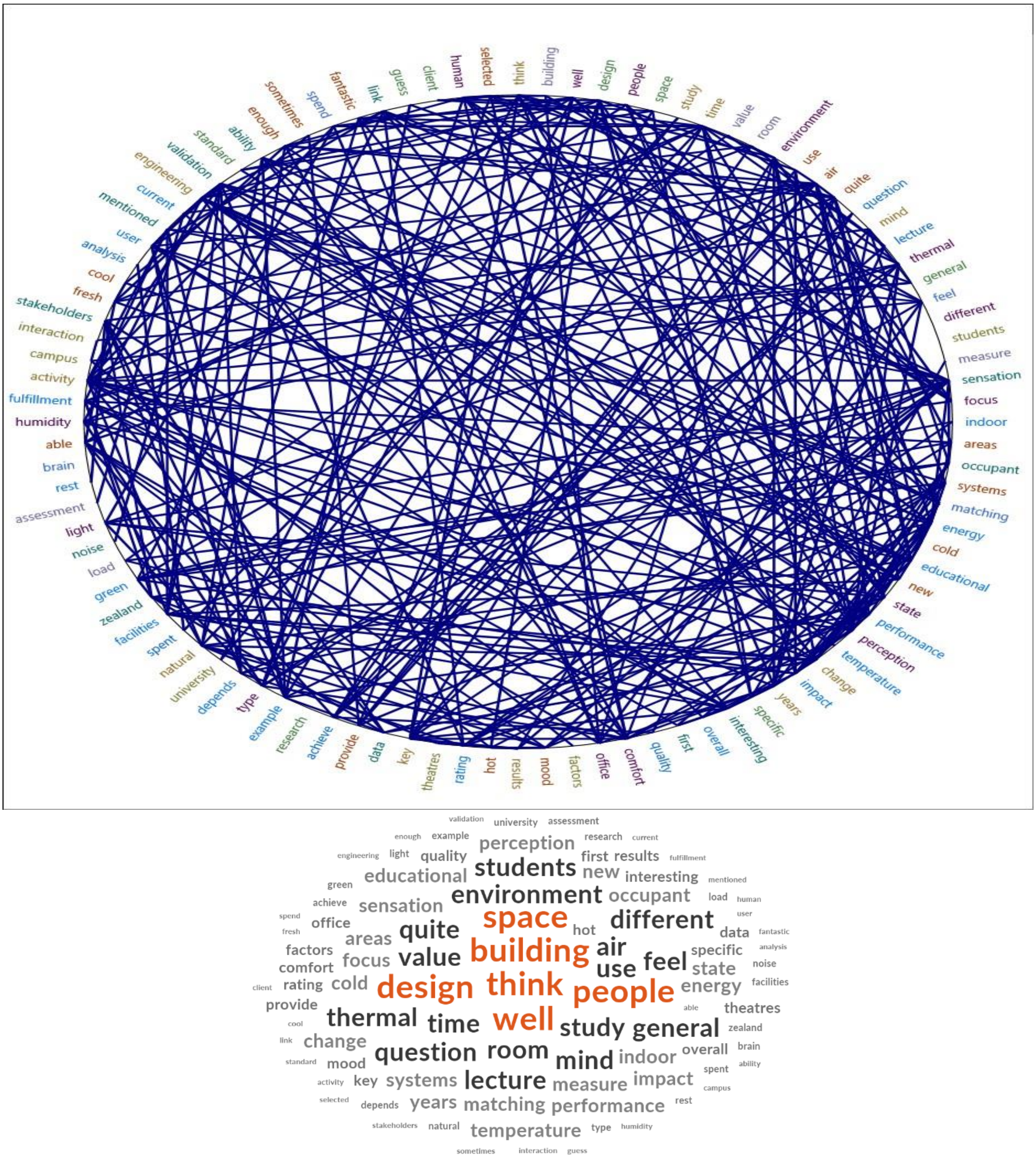
- Incorporating Occupant Emotions: A growing interest exists in integrating occupant emotions and feelings into post-occupancy evaluations. This approach can yield valuable insights into building performance and occupant satisfaction.

- Tailored Design for Different Spaces: Tailoring design purposes to specific spaces within a building was recognized as a promising approach. For instance, lecture rooms require different design considerations than open and quiet study areas.

In conclusion the interviews, have reached the saturation criteria and the research objectives, highlighted in section 2. The overall results of the interviews are highlighted in table 3. Additionally, Figure 5 illustrate the key points of discussion, using a word visualization of the interviews' scripts.

Table 3: Summary of the interview results against the research objectives

Research objectives	**Interview result**	**Remarks**
Identify the significance of ITC for the occupant's state of mind.	The quantitate data was verified by all interviewees.	Designers and engineers often focus on energy consumption more than ITC
Identify the most significant spaces and activities in educational buildings.	The quantitate data was verified by all interviewees.	Lecture room receives less attention during the design stage
Measure the impact of ITC in the identified space on the occupant's performance.	All interviewees emphasised that it is much needed, and there is major gap in post occupancy assessments.	Office building are more feasible for such assessment, as the result would increase productivity.



*30 **Figure 5.5:** Text analysis of the interviews script.*
This analysis, using NVivo 12 software, highlights the significant keywords and visualise their relative links.

5.4 The brain mapping experiment

In this experiment, we used EEG recordings to examining changes in brain activity associated with moderate alterations in indoor thermal conditions. The participants were exposed to two different thermal variations measured by controlled change in PMV (controlled by temperature and humidity), and by ventilation (natural vs. closed). During the experiment, participants watched a lecture recording while seated comfortably in a chair in a temperature-controlled room. Continuous EEG data recording was taking place while they watched the lecture recording.

5.4.1 Experiment design

The experiment design, as shown in Figure 5.6, is to isolate the key parameters in ITC and measure their variation against the occupant's performance (measured against the preferred state of mind identified in section 3). Accordingly, and after the consultation and approval of the university's ethics committee, the participants were invited to the allocated lecture room. Over a period of six weeks the research team have collected data from 22 participants. Each participant's performance was recorded, for approximately 30 minutes, by EEG scanner against two variations of ITC; ventilation (open vs closed) and PMV. The experiment variables and instruments are summarized in table 5.3.

*23 **Table 5.3:** Summary of the used instruments and experiment variable*

Instruments	EMOTIV EPOC+ 14 Channel Mobile EEG. Delta Ohm HD35 – Wireless Data Logger System. Delta Ohm HD32.1 – Thermal Microclimate Data Logger (5 probes).	
Independent variables	Participant's brain mapping results (EEG Recordings). The main recorded waves are: Theta (θ) 4-8 Hz, Alpha (α) 8-12 Hz, Beta (β) 12-25 Hz, and Gamma (γ) 25-45 Hz.	
	Experiment A	**Experiment B**
Dependent variables	IAQ, indicated by natural Vs closed ventilation.	PMV indicated by. Operative Temperature (°C) Relative humidity (RH%).
Constant	Operative Temperature (°C) Relative humidity (RH%). Light Intensity (Lux).	Ventilation (closed) Light Intensity (Lux)
Range	Open and closed ventilation	RH% between 30-70 %, Operative Temp 18-26 °C

The participants arrived in the designated classroom and following a brief explanation of the experiment's procedures and equipment, the research team assisted them in putting on the EEG scanners. After that, they were instructed to watch a lecture about a general course of study, i.e., academic writing. Initially the room temperature was set up to the outdoor temperature in closed ventilation and after 5 minutes of recording the research team opened room windows for 5 minutes, to measure the variation between closed and open ventilation. During the second part of the experiment, to measure the actual brain function recorded in different ITC levels (measured by PMV), the research team altered the thermal comfort parameters (i.e., temperature 18–26 °C and humidity 30–70%) while recording the corresponding brain mapping waves and PMV. The timeline of the experiment and the devices used are summarized in Table 5.4.

*24 **Table 5.4:** breakdown of the timeline of the experiment*

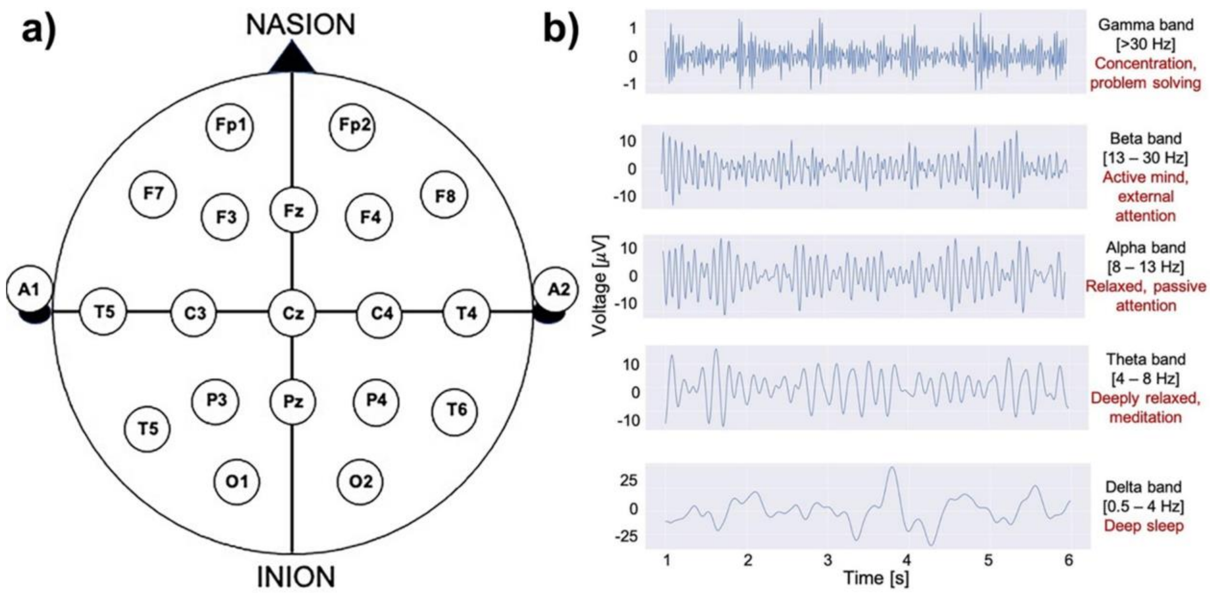
Time interval	**Description**
Minute 0-10	General introduction to the experiment and the devices. Setting the EEG recording device on the participant 's head. Recording the participant's data for PMV, e.g., clothing type, age, gender, approximated weight, etc. Playing a lecture recording to stimulate the lecture room.
Minute 10-20	Experiment A: 5 minutes closed ventilation – then open the windows and record the open ventilation for 5 minutes
20 -25	Closing the window and setting the temperature to 18°C
Minute 25-40	Experiment B: Increasing the temperature with increments of 1 degree to 26°C
Minute 35-40	Assisting the participant to remove the recording device and briefly discussing the results with the participants.

5.4.2 Material and methods of measurement

This section focuses on the brain mapping recording (EEG) and the thermal environment monitoring, while the subject performance in the ventilation part of the experiment is directly measured against on/off variable (i.e., open vs closed).

5.4.2.1 Brain mapping recordings

When populations of neurons that are oriented in parallel are synchronously active, their electrical signals can be measured with electrodes placed on the scalp. (EEG); records and amplifies these electrical signals over time. For example, when we perceive a picture, populations of neurons in our brain respond to this picture. This response is measurable as a change in voltage at the scalp before, while and after seeing the picture (Gegenfurtner et al., 2017; Misulis, 2013; Nidal and Malik, 2014). EEG is considered the most common instrument for functional mapping and real-time brain wave scanning, as it is generally available in the market and easy to operate (Cruz-Garza et al., 2017; Radüntz, 2018). The EEG signal oscillation is rhythmic; thus, it is typically described in terms of bands of different frequencies, (Duffy et al., 1979; Gevins and Rémond, 1987; Nuwer et al., 1999; Quiroga and Schürmann, 1999), as shown in Figure 5.6.



*31 **Figure 5.6:** EEG Electrodes and signals.*
On left (a); the international 10–20 positioning system; Odd electrode numbers are on the left hemisphere, even electrode numbers on the right hemisphere. Letters correspond to lobes–F(rontal), T(emporal), P(arietal), and O(ccipital). C stands for Central, adopted from (Maskeliunas, Damasevicius, Martisius, and Vasiljevas, 2016). On the right (b): Output of measured brain waves voltage and frequency and their main indication (Mansi et al., 2021).

Using a 16-channel system and electrode placement that followed the international 10–20 electrode distribution system, EEG recordings were obtained. After scanning the human brain, the data collected from the various electrodes are processed to identify the brain activities, that reflect the state of mind, by the measurement of five main waves. All the reviewed EEG devices work according to the previously described methodology. The main difference is the electrode type (active or passive), numbers and positioning (Maskeliunas et al., 2016). However, they all are following the International 10–20 and 10–10 positioning system, See Figure 5.6.

Another different between available devices is; the embedded processing software that includes different signal filters to artefacts which occurs due to electrode movement, physical movement, optical movement and more widely reported; Muscle electrical activity (Islam et al., 2016; Brenton W McMenamin et al., 2010; Olbrich et al., 2011). Although there are several studies in the literature for effective detection and filtration of the EEG signals (Islam et al., 2016; Kumar, Sharma, and Tsunoda, 2017; Weiss et al., 2017), that were adopted in or data processing stage, see section 5.4.6.

The selected device, EMOTIV EPOC+14 channel has the following electrode orientation for 14 channels: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4, with two references: (Common Mode Sense/ Driven Right Leg) CMS/DRL references at P3/P4; left/right mastoid process alternative. It has a bandwidth of 0.16 – 43Hz, digital notch filters at 50Hz and 60Hz. According to (Cruz-Garza et al., 2017; David Hairston et al., 2014; Radüntz, 2018) the selected device is more convenient and had higher ratings when compared with other available devices. Even with a higher comfort level, EPOC had a higher overall preference based on the user's rating for data provided by each device (Cruz-Garza et al., 2017).

With the selected device, in our experiment, we will use EmotivPro software, licenced kit, and BrainViz. Both software will provide a high level of data and imagining that will allow us to accurately detect the minor changes in the subject state of mind, while guaranteeing the subject comfort. This high time resolution and depth of readings will be adequate to plot the impact of the change in our controlled variables on the human state of mind of the subject.

5.4.2.2 Thermal environment monitoring (PMV)

The controlled variables are measured by two instruments; Delta Ohm HD35 – Wireless Data Logger System and Delta Ohm HD32.1 - Thermal Microclimate Data Logger (5 probes). While the ITC will be altered by the change of humidity and temperature, the measured controlled variables are all the parameters of the predictive mean vote PMV, to normalise the thermal comfort. The PMV as presented in International Standard ISO 7730 (ISO, 1994, 2005a), is probably the most commonly used index of thermal comfort to evaluate modest indoor thermal environments (Földváry Ličina et al., 2018; Taleghani et al., 2013; Zomorodian et al., 2016) and is established based on following equations:

$$PMV = \left[0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028\right] \cdot \left\{ \begin{array}{l} (M-W) - 3{,}05 \cdot 10^{-3} \cdot \left[5\,733 - 6{,}99 \cdot (M-W) - p_a\right] - 0{,}42 \cdot \left[(M-W) - 58{,}15\right] \\ -1{,}7 \cdot 10^{-5} \cdot M \cdot (5\,867 - p_a) - 0{,}0014 \cdot M \cdot (34 - t_a) \\ -3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl}+273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{array} \right\} \quad (1)$$

$$t_{cl} = 35{,}7 - 0{,}028 \cdot (M-W) - I_{cl} \cdot \left\{3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl}+273)^4 - (\bar{t}_r+273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\} \quad (2)$$

$$h_c = \begin{cases} 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \end{cases} \quad (3)$$

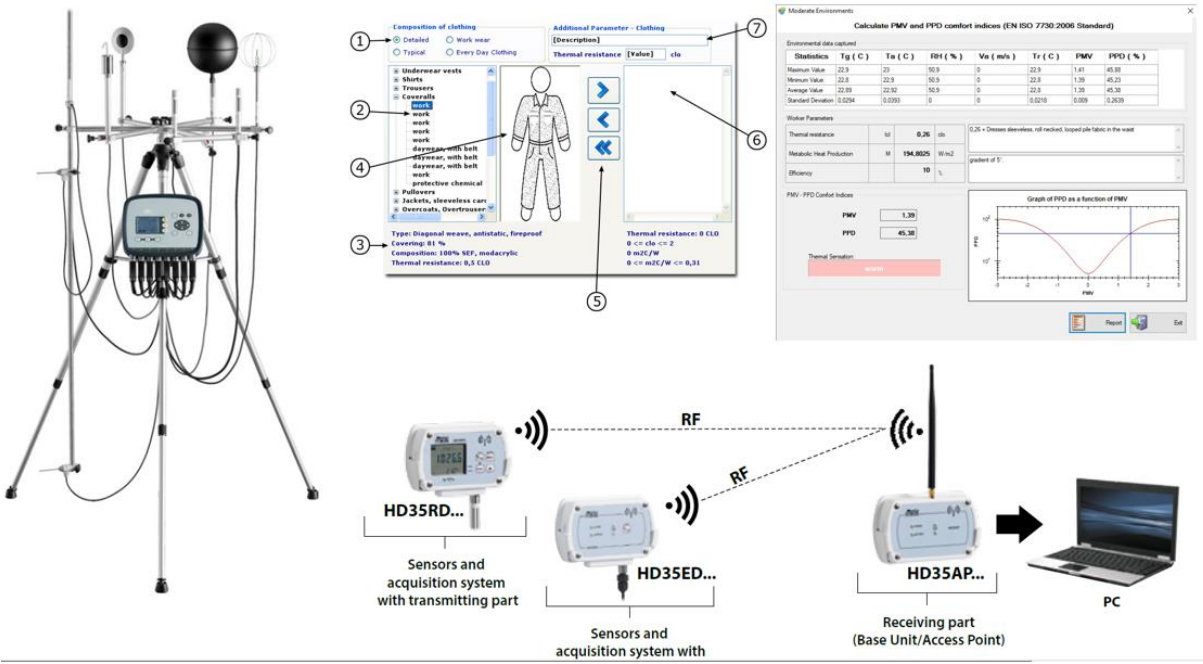
$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290\, I_{cl} & \text{for } I_{cl} \leqslant 0{,}078 \text{ m}^2 \cdot \text{K/W} \\ 1{,}05 + 0{,}645\, I_{cl} & \text{for } I_{cl} > 0{,}078 \text{ m}^2 \cdot \text{K/W} \end{cases} \quad (4)$$

where

- M is the metabolic rate, in watts per square metre (W/m^2);
- W is the effective mechanical power, in watts per square metre (W/m^2);
- I_{cl} is the clothing insulation, in square metres kelvin per watt (m^2 · K/W);
- f_{cl} is the clothing surface area factor;
- t_a is the air temperature, in degrees Celsius (°C);
- $\bar{t}_r$ is the mean radiant temperature, in degrees Celsius (°C);
- v_{ar} is the relative air velocity, in metres per second (m/s);
- p_a is the water vapour partial pressure, in pascals (Pa);
- h_c is the convective heat transfer coefficient, in watts per square metre kelvin [W/(m^2 · K)];
- t_{cl} is the clothing surface temperature, in degrees Celsius (°C).

NOTE 1 metabolic unit = 1 met = 58,2 W/m^2; 1 clothing unit = 1 clo = 0,155 m^2 · °C/W.

The main measurement of thermal comfort in our experiment, PMV, depends on several measured and estimated parameters. Recently, few scientific instrument combined with software have been developed, to accurately indicate the PMV directly from the measured parameters, via the appropriate probs and the subject data, such as Delta Ohm Thermal Microclimate HD 32.1 (Asere et al., 2016; Gendelis et al., 2017). The proposed measuring equipment (Delta Ohm HD32.1 – Thermal Microclimate Data Logger - 5 probes) has all the required sensors for measuring the PMV, the provided Delta Ohm software of the instruments also has built in algorithm to estimate the PMV, based on the subject biological, and clothing data, see Figure 5.7.



*32 **Figure 5.7:** Environmental monitoring instruments and software used to record PMV.*
Based on participants clothing and biological data. The software estimates the PMV according to UNI EN ISO 7730: "Moderate Environments Determination of the PMV and PPD indices and specification of the conditions for thermal comfort" and UNI EN ISO 8996: "Ergonomics - Determination of metabolic heat production".

To minimize the external stimulus on the subject state of mind, each subject will wear their choice of comfort clothing. The clothing isolation factor (I_{cl}), for each subject, was calculated and inserted into the instrument's software; DeltaLog 10, along with the metabolic rate, to compute the accurate PMV. The metabolic rate of each subject is calculated based on their gender, age, weight and height (Lighton, 2018; Mann and Truswell, 2017), and according to UNI EN ISO 8996: "Ergonomics - Determination of metabolic heat production" .

5.4.3 Participants

Over six weeks twenty-two students and university staff have volunteered to participate in the experiment, the demographic breakdown as per table 5.5. The demographic breakdown of the participants is considered adequate representation of the university overall demographic distribution. According to the consent documents that were gathered, the participants were healthy adults who had no history of neurological, psychiatric, or other medical conditions.

*25 **Table 5.5:** Demographic breakdown of the twenty-two participants*

Gender	Male	13
	Female	9
Age	18-21	4
	22-25	8
	25-28	6
	28-31	4

In this study, we targeted participants to represent frequent users of higher educational buildings. Accordingly: on the final page of an earlier survey, participants were asked if they would be interested in taking part in the experiment. They then registered their interest online. Additionally, an advertisement was posted on the university's digital blackboard. All participants signed and returned a consent form, with accordance to the university's ethic committee requirements, to the researcher along with the following information: name, age, gender, and preferred time for the experiment.

5.4.4 EEG Analysis

Raw EEG signal is a weak signal with very low amplitudes and is generally contaminated by artefacts and noises. Therefore, pre-processing of the raw EEG signals is mostly carried out to remove artefacts and noise (Kumar et al., 2017). During the subject brain mapping many artefacts occur due to electrode movement, physical movement, optical movement and more widely reported; Muscle electrical activity (Islam et al., 2016; Brenton W. McMenamin et al., 2010; Olbrich et al., 2011). There are several studies in the literature for effective detection and filtration of the EEG signals (Islam et al., 2016; Kumar et al., 2017; S. A. Weiss et al., 2017). To overcome the technical, mentioned, limitation of EEG, the experiments settings were designed to minimise these artefacts, by:

- Static environment, no movement or interruption of external stimulus to reduce the contamination of artefacts on the recorded signal.
- The recording setting for each subject will be limited to 15 minutes to avoid the drying of EEG electrodes and maintain the signal strength up to 95%.

Additionally, the following data analysis were conducted to ensure the quality of results: Filtering, Removal of artifacts, Epoching, Baseline correction, Re-referencing, and Artifact rejection. These pre-processing steps are essential for enhancing the interpretability and reliability of EEG data, allowing further analysis of the underlying brain activity with greater accuracy. The data recording, as shown in Figure 5.8, were extracted into a spread sheet. Using data analysis software, NCSS statistical software, all recordings were integrated against the PMV values, and the following statistical coloration analysis were conducted.

- Pearson Correlation Confidence Interval
- Spearman Rank Correlation Confidence Interval Section
- Pearson Correlation Test Section

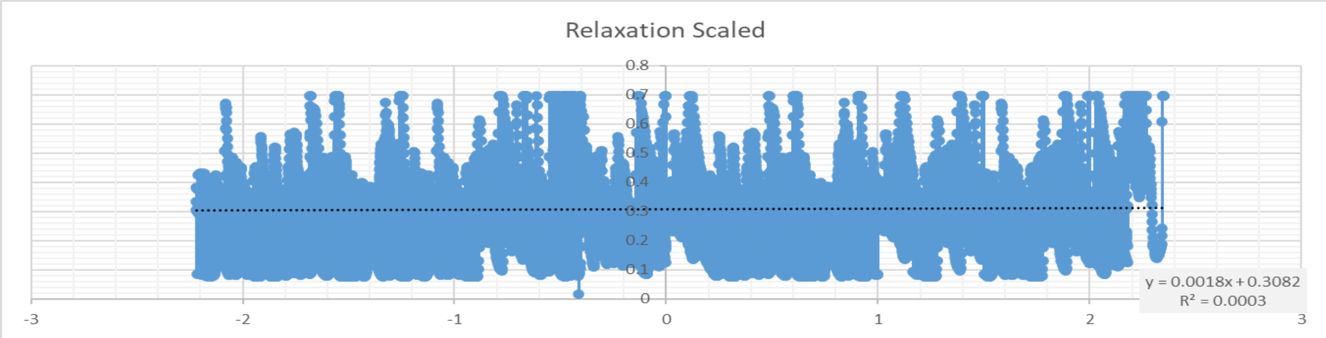
The integrated data analysis was conducted for each of the main 6 state of mind that were extracted from the EEG data.

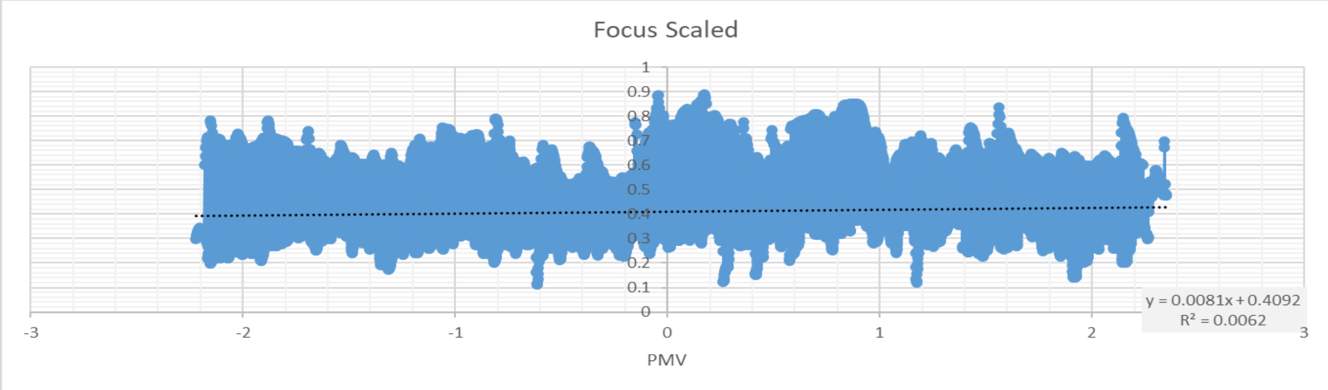
5.5 Results

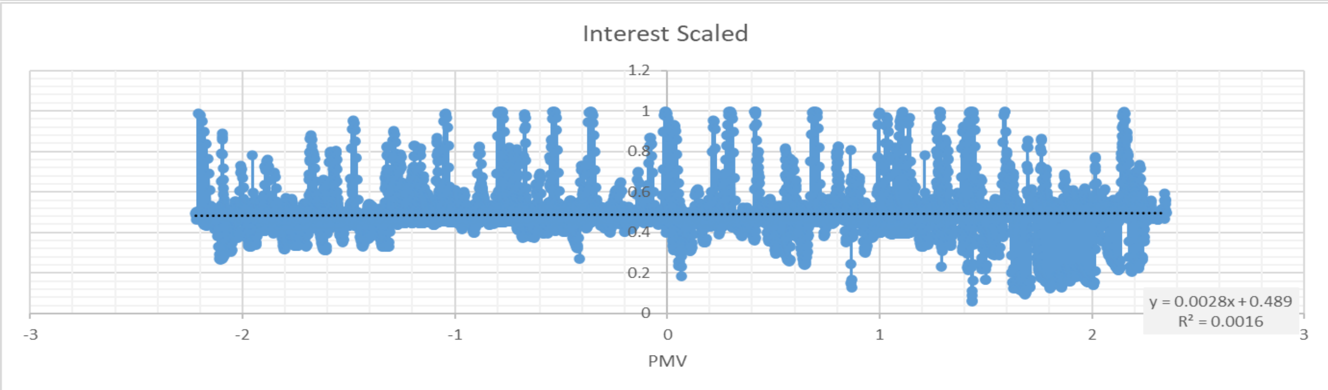
Each of the scaled state of mind were statistically analysed against PMV as described in section 4.6. The results, as summarised in table 5.7, indicates high statistical significance of each state of mind against PMV. The scaled values of the integrated data for each mental state column were plotted against PMV. The Scaled columns shows the Raw value scaled to fit on a 0 to 1 scale to provide more context for each individual's scores, see Figure 5.9. The scaling is based on a successive approximation of the mean and variance for each recording, calculated as the session progresses.

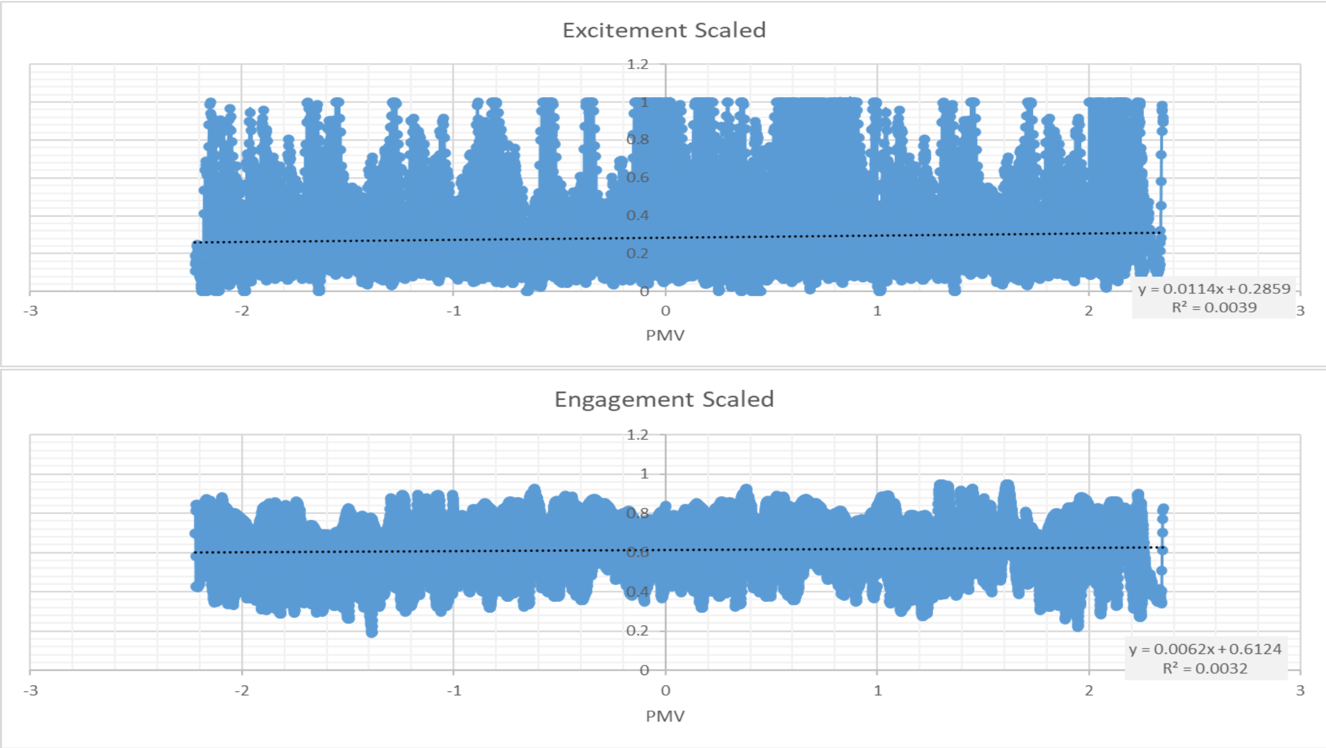
26 ***Table 5.6:*** *Summary of the statistical analysis of all variables.*

Variable		**Count**	**Mean**	**Standard Deviation**	**Min**	**Max**
Focus_Scaled		13653	0.41	0.13	0.11	0.89
Engagement_Scaled		13663	0.51	0.14	0.19	0.95
Relaxation_Scaled		13663	0.32	0.17	0.08	0.7
Interest_Scaled		13663	0.49	0.09	0.06	1
Stress_Scaled		13653	0.43	0.13	0.25	1
PMV		13653	0.04	1.27	-2.22	2.35
Pearson Correlation Confidence Interval Section – Against PMV						
			R Distribution-95% Confidence Limits		**Normal Approximation-95% Confidence Limits**	
	Pearson Correlation	**Count**	**Lower**	**Upper**	**Lower**	**Upper**
Focus	0.0788	13653	0.0621	0.0955	0.0621	0.0955
Engagement	0.0933	13663	-0.0767	-0.1099	-0.1099	-0.0767
Relaxation	0.1135	13653	0.0969	0.13	0.0969	0.13
Interest	0.0712	13653	0.0545	0.0879	0.0545	0.0879
Stress	0.1496	13653	0.1331	0.1659	0.1332	0.1659
Spearman Rank Correlation Confidence Interval Section - Two-Sided Confidence Interval - Against PMV						
		Normal Approximation - 95% Confidence Limits				
	Spearman Correlation	**Count**	**Lower**	**Upper**		
Focus	0.1701	13653	0.1537	0.1865		
Engagement	0.0682	13663	-0.0849	-0.0514		
Relaxation	0.0054	13653	-0.0114	0.0222		
Interest	0.3106	13653	0.295	0.326		
Stress	0.3426	13653	0.3273	0.3578		


Relaxation Scaled
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-3
-2
-1
0
1
2
3
y = 0.0018x + 0.3082
R² = 0.0003

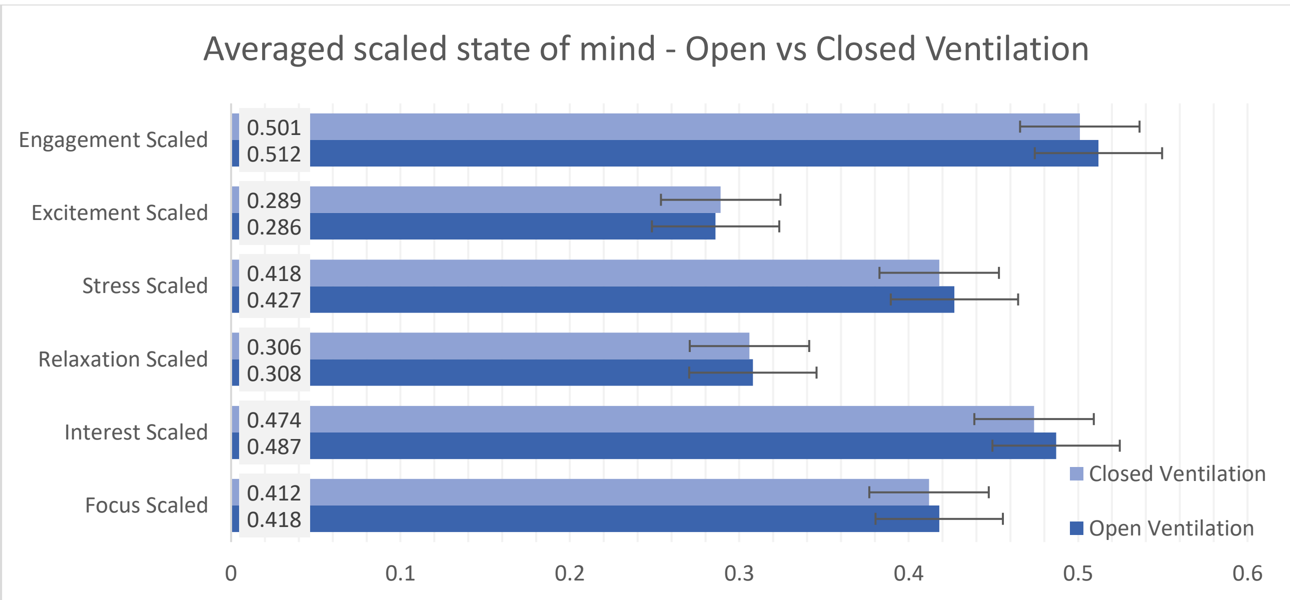

Focus Scaled
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-3
-2
-1
0
1
2
3
PMV
y = 0.0081x + 0.4092
R² = 0.0062


Interest Scaled
1.2
1
0.8
0.6
0.4
0.2
0
-3
-2
-1
0
1
2
3
PMV
y = 0.0028x + 0.489
R² = 0.0016



*33 **Figure 5.8:** Results of the scaled five mental states against PMV.*

The participants performance against the ventilation (closed vs open) was measured against an average PMV of 0.02 with lower limits of -0.21 and upper limits of 0.23. The variation of PMV during the recording was minimal and the participants did not notice the change in ventilation as the windows were located behind the participants. The results of each scaled state, as shown in Figure 5.9, showed a slight increase in the participant performance during open ventilation.



*34 **Figure 5.9:** Closed vs Open Ventilation against the scaled five mental states.*

5.6 Discussion

In this study, a mixed-method approach, incorporating EEG and behavioural data, was employed to investigate the effects of thermal conditions on individual subjects. The research objectives aimed to identify the significance of indoor thermal comfort (ITC) for the occupant's state of mind, determine the most significant spaces and activities in educational buildings, measure the impact of ITC on occupant performance in the identified spaces, and quantify the variation in ITC against performance. Throughout all the research stages, the significance of ITC on the occupant state of mind was certain as below conclusions from each stage.

5.6.1 *Survey discussion*

This survey focused on occupants' general thermal perception and did not include any building environment monitoring. This study focuses on the perceived thermal comfort. It did not include any quick questions and was not limited to a certain room. The participants were not instructed to complete the online survey in any specific location, as the study's goal is to assess the overall influence of the ITC on the occupant's state of mind (or perceived experience) beyond the temporal limitation of the exterior thermal stimuli.

The identification of the significance of indoor thermal comfort (ITC) in relation to other cognitive factors is a novel contribution of this study. To the best of our knowledge, there is a lack of comparable studies in the existing literature that directly compare ITC to other cognitive factors. Most of the reviewed studies focusing on the occupant's state of mind have predominantly employed behavioural or psychological approaches. Therefore, this study fills an important research gap by exploring the unique role of ITC in influencing the occupant's state of mind, offering valuable insights into the intersection of thermal comfort and cognitive factors. (Medlicott et al., 2021; O’Brien et al., 2020).

Another significant finding from the survey stage pertains to the importance of lecture rooms in determining the overall thermal performance of the selected building. The data revealed that lecture rooms held the highest median rating of 50, showcasing a 13% advantage over the second-rated location in terms of time spent. This highlights the prominent role that lecture rooms play in shaping occupants' thermal experiences within the building. Moreover, it is noteworthy that the lecture room was the only space that exhibited a substantial alignment between the overall thermal perception and the space-specific thermal perception, as indicated in Table 1. This suggests that occupants' perceptions of thermal comfort in the lecture room closely mirrored their overall perception of thermal conditions throughout the building. These findings underscore the significance of lecture rooms as focal areas for investigating and improving thermal comfort in educational buildings. Further analysis and discussion of these results will provide deeper insights into the specific factors influencing occupants' thermal experiences in lecture rooms and their implications for overall building performance.

The analytical findings of the survey regarding the state of mind preferences indicated no statistically significant difference between the preferred and perceived states of mind among the participants. This suggests that the provided building function, considering various interior design and operational factors, aligns well with the occupants' preferences. Although thermal comfort emerged as the most important component, it is important to note that the mood-related questions were framed in a way that encompassed all possible interior stimuli, reflecting a holistic perspective. These findings are particularly valuable for guiding the subsequent experimental stage, as they shed light on the function and purpose of educational buildings throughout the design and operational phases, as illustrated in Figure 5.4. By considering the broader context of interior design and operational factors, alongside thermal comfort, these findings provide insights into the multifaceted aspects that contribute to creating conducive learning environments. This understanding can inform decision-making processes and aid in optimizing the design and operation of educational buildings to better align with occupants' preferences and promote positive state of mind experiences.

5.6.2 Interview

According to the participants, the building's occupants are hardly considered, especially during the planning process. Post-occupancy surveys are extremely infrequent in New Zealand and are neither mandated nor encouraged by any evaluation instrument, including Green Start ratings. All agreed that there is a significant gap in building performance evaluation in New Zealand.

While everyone agreed that the lecture room was the most important to the occupants, it was not deemed crucial throughout the design process. To increase the energy performance of the building, designers frequently focus on energy-intensive places such as server rooms or labs. One participant even stated that the heat load and operational parameters for a lecture room are frequently predicted in under an hour. According to all operational specialists, the sole role of the occupants is to report a problem or failure of the AC system.

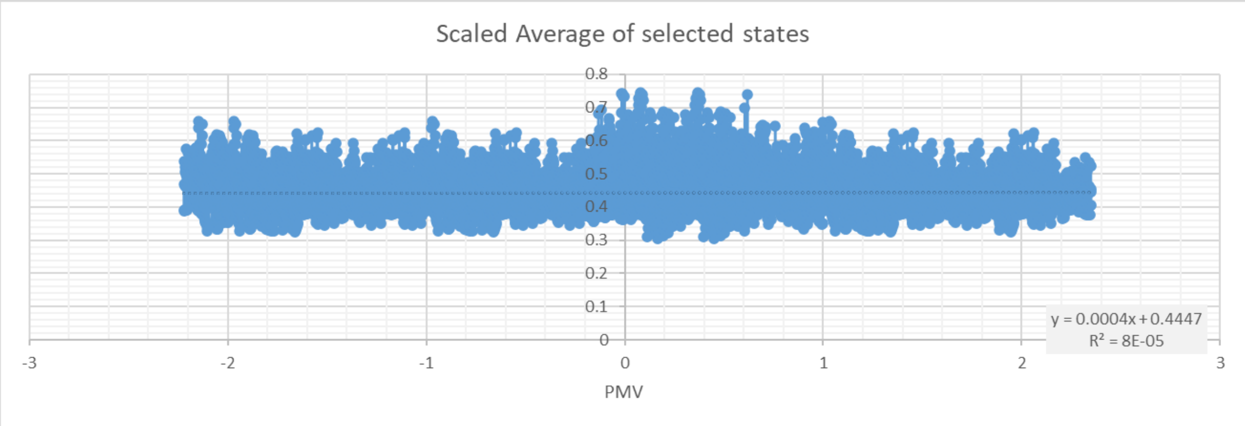
These findings from the interview stage, have further implications to the significance of our research topic. It highlights the crucial gap between the actual perceived experience of the occupants and the current built environment practices, that results in their surrounding environment. This gives further novelty to our study, as our experimental stage, in section 5.4, measures the occupant performance against the surrounding thermal environment.

5.6.3 Experiment discussion

Analysis of the participant excitement levels revealed that the highest peaks and magnitude were observed at positive PMV values. This finding could be attributed to the participants' thrill of being part of an advanced experiment and their engagement with the research process. However, it is important to note that the most preferred mental state, as indicated by the earlier survey, was found to be more significant in slightly warmer thermal conditions (PMV values of 0 to 1). This suggests that occupant performance tended to increase under these thermal conditions. Additionally, participants were more likely to experience a relaxed state in slightly cooler conditions (PMV values of -0.6 to -0.2). Interestingly, no significant variations were observed in engagement and interest states across different PMV values. This lack of variation could be attributed to the nature of the watched lecture, as a generic subject (i.e., academic writing) was selected to ensure the cohesion of participants' perception, regardless of their study background.

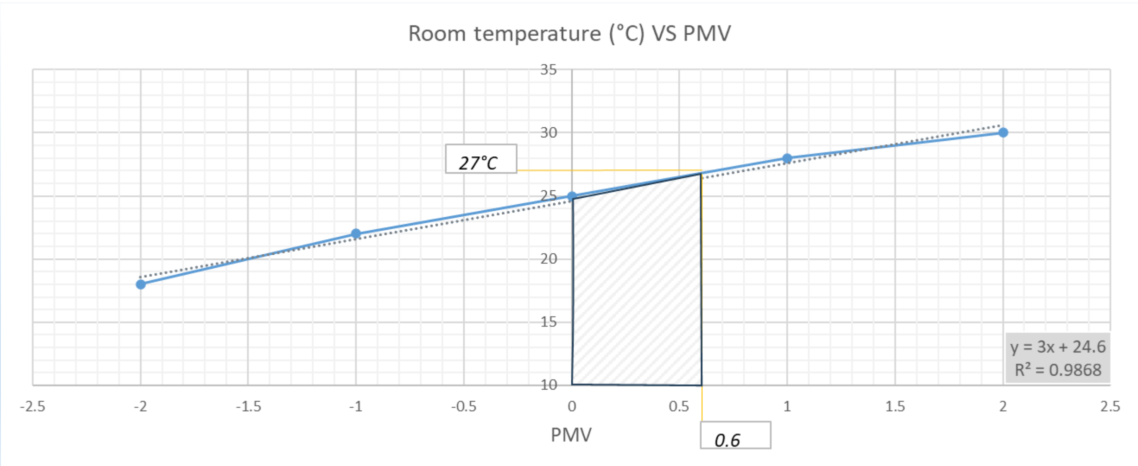
These initial findings shed light on the relationship between thermal conditions and occupant states of mind, with implications for creating optimal indoor environments in educational buildings. However, further analysis and interpretation are required to fully understand the nuanced effects of ITC on occupant performance and well-being in specific spaces and activities within educational settings. The findings, examining the potential underlying mechanisms and addressing the research objectives to provide a comprehensive understanding of the role of thermal comfort in enhancing occupant experiences and performance.

Furthermore, the state of mind results was scaled against the survey results to indicate the ultimate PMV range for the occupant performance. The results, as shown in Figure 5.10, showed significant increase in the participant performance in during PMV values of 0 to 0.6.



*35 **Figure 5.10**: Scaled average of the participant measured state of mind based on the preferred state of mind from the survey results, against PMV.*

These initial findings shed light on the relationship between thermal conditions and occupant states of mind, with implications for creating optimal indoor environments in educational buildings, as shown in figure 11. However, further analysis and interpretation are required to fully understand the nuanced effects of ITC on occupant performance and well-being in specific spaces and activities within educational settings. The findings, examining the potential underlying mechanisms and addressing the research objectives to provide a comprehensive understanding of the role of thermal comfort in enhancing occupant experiences and performance.



*36 **Figure 11:** Averaged room temperature against PMV for all participants*

The results of the statistical analysis indicate a significant relationship between the participants' state of mind and their performance in educational buildings, particularly in relation to indoor thermal conditions. Notably, the analysis revealed that higher performance levels were observed during open ventilation, indicating that increased air movement and fresh air circulation had a positive impact on occupant performance. This suggests that adequate ventilation may contribute to a more favourable indoor environment for educational activities. Furthermore, the study found that the participants' performance was also influenced by the Predicted Mean Vote (PMV) range of 0 to 0.6. Within this PMV range, which represents a thermally comfortable environment, participants exhibited higher levels of performance. This finding highlights the importance of maintaining appropriate thermal conditions within educational buildings to optimize occupants' performance. Implementing strategies to ensure proper ventilation and maintaining thermal comfort levels within this range can contribute to creating a conducive environment for learning and achievement.

The main limitation in this study is the dependence on the PMV scale. While the PMV model is widely used in the design and operation of buildings to ensure optimal thermal comfort levels. Which is founded on the idea that thermal comfort can be attained when the heat generated by the body and the heat dissipated into the environment are in balance (Broday et al., 2019). The model calculates a numerical score that represents the predicted mean vote of the group. Additionally, it has undergone considerable validation through field tests (Hasan et al., 2016). The PMV model has, however, been criticised for its limitations, notably the fact that it dismisses individual variability in thermal sensitivity as well as the influence of non-thermal elements like psychological and social factors on thermal comfort (Broday et al., 2019). Despite these limitations, PMV remains a widely used method for assessing thermal comfort due to its simplicity and effectiveness in forecasting thermal comfort levels in various environments.

The results indicated a slight change in the participants performance, measured against their preferred state of mind in educational buildings, with higher performance recorded in open ventilation and PMV range of (0 to 0.6). While these changes are slightly significant it has greater implications over the overall thermal performance of the building, as indicated in the survey stage, the occupants were aware of the impact of ITC on their state of mind. Moreover, thermal comfort is crucial in educational facilities as it has an impact on attendance rates, academic achievements, and the attitudes of both students and teachers (Lamberti et al., 2021; O'Brien et al., 2020). Inadequate thermal comfort can result in discomfort, diversion, and decreased concentration, all of which can have a negative effect on learning outcomes (Lamberti et al., 2020).

5.7 Conclusion

This research provides novel insights into the impact of indoor thermal variation on occupants' state of mind and performance in educational buildings. It contributes to the field of architectural science by presenting unique findings and recommendations for designing optimal indoor environments in educational settings.

The novelty of this research lies in its comprehensive investigation, employing advanced scientific measurements, focusing specifically on educational buildings in New Zealand. To the best of our knowledge, this study is the first of its kind in New Zealand, making it a pioneering contribution to the field.

Key findings from this research include:

- Participants exhibited higher performance levels during open ventilation, highlighting the importance of adequate airflow and fresh air circulation in educational buildings.
- Optimal occupant performance was observed within the Predicted Mean Vote (PMV) range of 0 to 0.6, emphasizing the significance of maintaining thermal comfort conditions within this range.

Comparing these findings with previous studies, we note that they align with existing research highlighting the positive impact of ventilation and thermal comfort on occupant performance. However, our study provides specific insights applicable to educational buildings in the New Zealand context, offering valuable guidance for architectural design in this setting.

The design implications derived from this study include:

- Architects should prioritize effective ventilation systems or natural ventilation strategies to enhance air movement and circulation in educational buildings.
- Maintaining thermal comfort within the PMV range of 0 to 0.6 should be a design goal, achieved through insulation, efficient HVAC systems, and temperature regulation.

The knowledge contribution of this study is significant, as it integrates advanced scientific measurements with architectural science to optimize the thermal performance of educational buildings. By focusing on New Zealand's context and educational facilities, this research fills a gap in the current knowledge base and offers practical guidelines for architects and designers. The next step in this research would involve implementing the design implications derived from this study in real-world educational buildings and assessing their impact on occupant performance on wider sample. Further studies could explore the long-term effects of improved thermal conditions on occupants' learning outcomes and academic achievements.

In conclusion, this research provides valuable insights into the relationship between indoor thermal conditions, state of mind, and performance in educational buildings. Its novelty lies in being the first study of its kind in New Zealand, with specific implications for architectural design in educational settings. The findings highlight the importance of ventilation, thermal comfort, and their impact on occupant performance, offering practical guidelines for creating optimal indoor environments. Future studies can build upon these findings to advance our understanding and contribute to the field of architectural science.

Chapter 6 – Discussion, Conclusions and Recommendations

6.1 Overview

This conclusion chapter synthesizes the key findings and discussions from four research papers that collectively contribute to our understanding of the relationship between indoor thermal comfort (ITC), occupants' experiences, and building performance. It encapsulates the insights gathered from four distinct research papers, each contributing to a comprehensive understanding of the symbiotic relationship between indoor thermal comfort (ITC), the occupant's experiential realm, and the overarching landscape of building performance. By delving into various facets of ITC across diverse building types, with a particular emphasis on educational settings, this study employed a multifaceted approach. This methodology integrated literature reviews, surveys, interviews, experiments, and advanced scientific measurements to unveil the profound impact of ITC on occupants' holistic well-being, performance, and cognitive states.

6.2 Key Findings and Discussion

The research findings revealed several significant insights into the influence of ITC on occupants' experiences. In Chapter 1, the limitations of the existing building assessments were identified, emphasizing the need for a more comprehensive understanding of the perceived occupant experience and its impact on building performance. Chapter 2 explored the neuropsychological significance of ITC through brain mapping studies, highlighting the activation of distinct brain regions in response to thermal variations. This revealed the inadequacy of current thermal indices in fully capturing the neuropsychological effects of thermal sensation, leading to the proposal of a novel framework that integrates PTC into building performance assessments.

Chapter 3 focused on educational buildings in Auckland, New Zealand, and quantified the impact of ITC on occupants' experiences through a survey-based study. The results indicated that ITC was the most significant factor influencing occupants' mood or mental state, surpassing cognitive factors. The lecture room emerged as a critical space for thermal perception, suggesting the need for targeted research in this area. Importantly, the study found a level of alignment between occupants' expectations and actual experiences, highlighting the potential for optimizing conditions for student learning within educational environments.

Building upon the findings of Chapter 3, Chapter 4 delved deeper into the methodology, findings, and implications of the study in educational buildings. The chapter proposed a mixed-method approach that combined qualitative and quantitative methods to measure the impact of ITC on occupants' performance and quantify the variation in ITC against occupants' performance. The research demonstrated the significance of ITC on occupant performance in educational buildings, particularly within the PMV range of 0 to 0.6. Even though the range is close to the current PMV module, the measured occupant’s performance with significantly proportional to the thermal environment.

6.3 Fulfilment of Research Aims and Objectives.

The objectives of this research, as outlined below, have been meticulously pursued and fulfilled through a multi-faceted investigation into the intricate interplay of indoor thermal comfort, occupants' experiences, and building performance. In doing so, this study has effectively achieved its overarching aim of comprehensively investigating the impact of indoor thermal variation on occupants' state of mind and performance in educational buildings. This overarching aim was guided by the core objective of shedding light on the complex relationship between indoor thermal conditions, occupant satisfaction, and performance, with a specific and keen focus on the creation of optimal indoor environments within educational settings.

Objective 1: Identify and Quantify the Significance of ITC for the Occupant's State of Mind

The first objective of this research aimed to delve into the extent of indoor thermal comfort's influence on the occupant's state of mind. This objective recognized that thermal comfort transcends mere physical sensations to significantly impact occupants' emotional and psychological well-being. Through meticulous exploration, the research sought to uncover the degree to which indoor thermal comfort shapes occupants' mood and mental states. By synthesizing multiple research methodologies, including brain mapping studies and surveys, this research effectively quantified the importance of indoor thermal comfort in influencing occupants' holistic experiences, subsequently fulfilling the first objective.

The investigation into neuropsychological aspects (Chapter 2and3) laid the foundation for recognizing that ITC transcends a mere physical phenomenon, deeply influencing emotional states through its impact on the central nervous system. Furthermore in (Chapter 3); it was evident that, the controlled variation of the surrounding thermal environments effectuated alterations in the brain activity. This variation, of the surrounding thermal conditions, included six brain areas and all the main five brain wave frequency bands. Additionally, the reported studies revealed that; the same neural channels can process the warm and cold stimulations differently, which results in the variation of the EEG patterns, and consequently impact the occupant state of mind.

Building upon this foundation, the survey-based study (Chapter 4) underscored ITC's central importance, demonstrating that it holds a higher influence over occupants' mood and mental state than cognitive factors. The key finding was that the students were exceptionally aware of their mood changes (55.1%) due to ITC compared to other key conscious/cognitive factors (i.e., study load 48.3%, interaction with colleagues 29.2%, etc.). There was not any acknowledged study in the literature that compared the thermal perception to other cognitive factors that may impact the occupant’s actual, and perceived experience.

By substantiating the linkage between thermal comfort and mental well-being, this research effectively quantified the significance of ITC, meeting the first objective.

Objective 2: Investigate and Measure the Impact of Indoor Thermal Variation on Occupants' State of Mind and Performance in Educational Buildings

The second objective revolved around delving into the impact of variations in indoor thermal conditions on occupants' state of mind and their subsequent cognitive performance within educational buildings. This objective recognized that changes in temperature could have intricate repercussions beyond mere thermal sensation, possibly influencing how individuals think, feel, and perform. Through a meticulous blend of qualitative and quantitative methods, including experimentation and survey-based analysis, this research successfully proofed and measured the interplay between indoor thermal variations and occupants' mental and cognitive states.

The meticulous exploration conducted across multiple stages of this research has successfully unravelled the intricate relationship between indoor thermal variation, occupants' mental states, and their subsequent performance. Through the advanced EEG experiment (Chapter 5), this research exposed a compelling correlation between indoor thermal conditions and the occupant's mental and cognitive states.

The experiment data and analysis showed direct variation of the measured state of mind against the indoor thermal environment. The participants performance against the ventilation (closed vs open) was measured against an average PMV of 0.02 with lower limits of -0.21 and upper limits of 0.23. The results of each scaled state, as shown in Figure 5.9, showed a slight increase in the participant performance during open ventilation.

While there were no significant variations observed in engagement and interest states across different PMV values. The participants showed significant variations against three of the key preferred states of minds, as identified from the survey in (Chapter 4). The measured variations are:

- The participant excitement levels revealed that the highest peaks and magnitude were observed at positive PMV values.
- The Focus levels was found to be more significant in slightly warmer thermal conditions (PMV values of 0 to 1).
- Participants were more likely to experience a relaxed state in slightly cooler conditions (PMV values of -0.6 to -0.2).

By measuring the empirical impact of indoor thermal variation on occupants' performance within educational buildings, this research effectively fulfils the second objective. This, in turn, contributes to the broader understanding of the dynamic interplay between indoor environmental quality, occupants' psychological states, and cognitive performance.

Objective 3: Identify Critical Spaces within Educational Buildings that Significantly Influence Thermal Performance and Preferred Mental States Conducive to Improved Performance

The third objective sought to identify the specific spaces within educational buildings that wield substantial influence over thermal performance and preferred mental states conducive to enhanced cognitive performance. Recognizing that not all spaces contribute equally to occupants' well-being and performance, this objective aimed to distil critical indoor environments that should be targeted for improvement.

Within the context of educational buildings, this research transcends generalities by identifying the specific spaces that wield the most influence over thermal performance and preferred mental states conducive to improved performance. By distilling these insights from surveys (Chapter 4) and thorough experimentation (Chapter 5), this research has effectively pinpointed lecture rooms as crucial environments that closely mirror occupants' overall thermal perceptions. Comparing the lecture rooms to other spaces, weighted to the overall time distribution between all other spaces, it scored the highest percentage of 27% from six different spaces.

The significance of the time spent (in section 4.4.1) was reflected in the thermal sensation in total vs lecture room. The thermal sensation in a lecture room, amongst all other indoor spaces, had the most significant match to the overall indoor thermal sensation, as shown in table 4.6. This further signify the importance of lecture room thermal settings on the overall thermal performance of educational buildings.

The successful identification of these critical spaces substantiates the third objective. These findings provide a targeted guidepost for architects and designers seeking to elevate the thermal quality of educational spaces and amplify occupants' well-being and performance.

Objective 4: Bridge the Gap Between User Expectations and Stakeholder Objectives by Aligning User Experiences and Preferences with the Design and Operation of Educational Buildings

The fourth objective was rooted in the recognition of a disconnect between user expectations and stakeholder objectives in building design and operation. It aimed to bridge this gap by harmonizing user experiences and preferences with the strategic goals of stakeholders. By advocating for an evidence-based approach that integrates perceived thermal comfort into building performance assessments, this objective sought to create a transformative paradigm shift where user well-being and cognitive harmony take centre stage. By identifying the alignment between user preferences and design principles, this research effectively realized the fourth objective, proposing a framework that prioritizes occupants' psychological well-being and elevates the human experience in educational buildings.

By illustrating the measured impact of ITC on occupants' well-being and performance, this research harmonizes user experiences with stakeholder objectives. The insightful findings (Chapters 4 and 5) serve as a clarion call for evidence-based design and operational practices that prioritize occupants' mental states. This, in turn, advances the fourth objective, advocating for a groundbreaking framework that integrates perceived thermal comfort into building performance assessments (Chapter 3). By aligning user preferences with the design and operation of educational buildings, this research contributes to a paradigm were building design embraces occupants' psychological well-being and cognitive harmony.

In this research, the state of mind results was scaled against the occupants' preferences survey results to indicate the ultimate PMV range for the occupant performance. The results, as shown in Figure 5.10, showed significant increase in the participant performance in during PMV values of 0 to 0.6. This finding is critical to any future educational building design, to optimise the building performance using user-centric approach.

In conclusion, the holistic exploration undertaken throughout this research journey not only fulfils each objective but also realizes the overarching aim of comprehensively investigating the impact of indoor thermal variation on occupants' state of mind and performance in educational buildings. By uncovering the intricate relationship between indoor thermal conditions, occupant satisfaction, and performance, this study addresses a critical gap in understanding and practice. Ultimately, the insights gleaned from this study serve as a compass guiding the creation of indoor environments that are not only energy-efficient but are also human-centric havens, nurturing well-being, productivity, and cognitive harmony within the educational context and beyond.

6.4 Contribution and Significance of the Research

This research makes several important contributions to the field of indoor environmental quality and building performance. Firstly, by integrating neuroscience, user perspectives, expert insights, and empirical measurements, it offers a more holistic understanding of the impact of ITC on occupants' well-being, performance, and state of mind. The findings emphasize the need to consider the neuropsychological aspects of thermal comfort and the occupants' unique thermal perception in the design, operation, and management of buildings.

Secondly, the research highlights the significance of ITC in educational buildings, where occupants' experiences and performance are crucial for achieving the building's purpose. By quantifying the impact of ITC on occupants' experiences, the research provides valuable insights for optimizing the thermal performance of educational buildings and creating better indoor environments for building users. The findings emphasize the importance of the lecture room as a critical space for thermal perception and suggest targeted research in this area.

Thirdly, the research contributes to the development of a novel framework that incorporates PTC into building performance assessments. By identifying the limitations of existing thermal indices and proposing a more comprehensive approach, the research offers practical implications for designing and evaluating buildings that promote mental health, well-being, and optimized performance.

6.5 Limitations

While this research provides valuable insights, it is important to acknowledge its limitations. Firstly, the research primarily focused on educational buildings in Auckland, New Zealand, which may limit the generalizability of the findings to other geographic locations and building types. Further studies in different contexts are needed to validate and expand upon these findings.

Secondly, the sample size of the survey-based study in Chapter 3 was limited to 109 participants, which may impact the generalizability of the results. Future research could involve larger and more diverse samples to enhance the representativeness of the findings.

Lastly, the research primarily utilized quantitative and qualitative methods, with a focus on self-reported measures and surveys. While these approaches provide valuable insights, future research could consider incorporating objective measures and longitudinal studies to further understand the long-term effects of ITC on occupants' experiences and performance.

Despite these limitations, this research significantly advances our understanding of the complex relationship between ITC, occupants' experiences, and building performance. The comprehensive approach, combining multiple research methods, enhances the validity and applicability of the findings, contributing to the development of evidence-based design principles and strategies for creating comfortable and high-performing indoor environments.

In conclusion, this research highlights the importance of considering the neuropsychological aspects of ITC and the occupants' state of mind in designing, operating, and managing buildings. The findings underscore the need for a holistic view of indoor thermal comfort, going beyond energy performance and incorporating occupants' distinctive thermal perception. By integrating these insights into future building standards, codes, and green building certifications, we can enhance occupant well-being, optimize performance, and create healthier and more comfortable indoor environments.

6.6 Implications and Future Directions

This research opens avenues for practical application and further exploration. The multifaceted methodology's robustness and inclusivity contribute to evidence-based design principles, driving the creation of healthier, more comfortable indoor environments. By integrating these insights into building standards, codes, and green certifications, we can elevate occupant well-being and performance.

This research accentuates the significance of embracing the neuropsychological aspects of indoor thermal comfort and the occupants' psychological states in the creation, operation, and management of buildings. The findings underscore the necessity for a comprehensive perspective on indoor thermal comfort, transcending energy performance and encompassing occupants' distinctive thermal perceptions. By embedding these insights into future building standards, codes, and green building certifications, the industry can augment occupant well-being, optimize performance, and cultivate healthier and more comfortable indoor environments.

The proposed novel framework integrating perceived thermal comfort (PTC) into building performance assessments paves the path for a transformative shift in the evaluation of indoor environments. This framework serves as a call to action for the development of more holistic building assessment indices that consider occupants' psychological well-being and cognitive performance alongside energy efficiency and sustainability metrics. This multidimensional approach will empower designers and stakeholders to create indoor spaces that holistically prioritize occupants' comfort, well-being, and cognitive engagement.

6.7 Recommendations for Future Research

This research's successful execution opens avenues for future explorations that can further deepen our understanding of indoor thermal comfort, occupants' mental states, and building performance. Potential areas for future research include:

Cross-Cultural Studies: Extending the scope beyond New Zealand to encompass diverse cultural contexts can provide insights into how cultural factors influence occupants' thermal preferences and psychological responses.

Longitudinal Studies: Conducting longitudinal studies to assess the long-term effects of indoor thermal comfort on occupants' psychological states and performance can shed light on the enduring impact of indoor environments.

Real-Time Monitoring: Implementing real-time monitoring of indoor thermal conditions and occupants' psychological states using wearable technology can offer continuous insights into the dynamic relationship between ITC and occupants' experiences.

<u>Comparative Analysis:</u> Comparing different building types (e.g., offices, residential, healthcare) in various geographic locations can uncover patterns in the relationship between ITC, occupant experiences, and building performance.

<u>Advanced Sensing Techniques:</u> Incorporating advanced sensing techniques, such as biometric measurements and eye-tracking technology, can provide a more nuanced understanding of occupants' cognitive responses to indoor thermal conditions.

6.8 Conclusion

In drawing the curtain on this research odyssey, we cement the significance of understanding indoor thermal comfort in a holistic context. The synergistic interplay between ITC, occupants' experiences, and building performance is undeniable. Through this research, we illuminate the intricate neuropsychological aspects of thermal comfort, advocate for its comprehensive integration into performance evaluations, and spotlight its pivotal role in educational settings.

As the global focus on occupant comfort, well-being, and sustainable design intensifies, the lessons gleaned from this research resonate deeply. The journey from literature review to brain mapping, from surveys to experiments, culminates in a resonating call for architectural and engineering paradigms that embrace occupants' psychological states as integral components of indoor environments. This research stands not only as a testament to progress made but also as a catalyst for future transformations, heralding a new era where buildings are designed not just as structures but as vessels of human well-being, comfort, and thriving.

As we collectively strive to create sustainable, healthy, and comfortable indoor environments, the insights garnered from this research serve as a guideline, leading us towards a future where buildings are not just energy-efficient, but also human-centric havens that nurture well-being, productivity, and cognitive harmony.

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