Exploring the Dynamics of Occupants' Thermal and Visual Perception, Physiological Responses, and Performance in Office Environments

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ABSTRACT

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Hamidreza Karimian

Understanding occupant comfort in indoor environments is critical for designing spaces that promote well-being and efficiency. However, traditional assumptions regarding occupants' thermal and visual preferences often result in energy inefficiency or discomfort. This thesis examines different approaches for acquiring occupant information—ranging from subjective feedback and physiological measurements—to better understand comfort preferences in varying environments.

Additionally, this work addresses the gaps in comfort research, which is predominantly focused on the Global North, by conducting experimental studies in contrasting climatic regions (Montreal, Canada - ASHRAE Climate Zone 6, and Cairo, Egypt - ASHRAE Climate Zone 2B). These studies investigate the interplay between thermal and visual comfort domains under varied lighting and temperature conditions and their impact on physiological responses such as heart rate variability (HRV) and skin temperature (ST). Furthermore, thermal comfort analyses were conducted using wearable sensing technologies to monitor physiological signals, including electroencephalography (EEG), HRV, and ST. These analyses assess how thermal conditions influence comfort perceptions and task performance across different genders and locations, revealing significant variations in physiological responses to temperature and lighting conditions. The experiments were conducted in controlled office environments to simulate real-world conditions, and the data collected aimed to evaluate location-specific and gender-related differences in comfort and performance.

Comparative analyses from experimental trials in Montreal and Cairo show notable differences in thermal comfort perception and task performance, with males being more sensitive to thermal conditions and location-specific variations affecting heart rate variability and skin temperature. These findings provide a foundation for developing adaptive building environments that can dynamically adjust indoor conditions to improve occupant well-being and energy efficiency.

These findings offer valuable insights into the relationship between physiological responses, thermal comfort perceptions, and occupant performance in office environments, offering a pathway toward the integration of Occupant-Centric Control (OCC) strategies in future smart building environment.

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I am also profoundly thankful to my wife, parents, and brother, whose steadfast support has been my foundation. Their encouragement, understanding, and love have provided me with the strength to persevere. Their dedication has been my greatest source of inspiration.

PREFACE

This thesis is based on three separate manuscript papers completed under the supervision of Dr. Mohamed Ouf, as part of the requirements for the Master of Applied Science in Building Engineering.

The following papers provide the foundation for this thesis:

1. "Sensing and Data Collection Methods for Occupant-Centric Building Control: A Critical Review of State of the Art": Presented at the Canadian Society for Civil Engineering (CSCE) 2021 Annual Conference; Karimian, H., Ouf, M., Cotrufo, N., Venne, J.
2. "Exploring the Dynamics of Thermal Perception, Physiological Responses, and Performance in Office Environments": Submitted to the journal *of Building Engineering*; Karimian, H., Ouf, M., Goubran, S.
3. "Examining the Impact of Location-Specific Variables on Occupant Comfort: A Comparative Study of Thermal and Visual Comfort in Cold and Hot Climates": Presented at the ASHRAE Winter 2024 Conference; Karimian, H., Ouf, M., Muhammad, R., Goubran, S.

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LIST OF ABBREVIATIONS

(Abbr.)	*Full Term*
(AR)	Augmented Reality
(ASHRAE)	American Society of Heating, Refrigerating and Air-Conditioning Engineers
(BAS)	Building Automation Systems
(BLE)	Bluetooth Low Energy
(CCT)	Correlated Color Temperature
(EEG)	Electroencephalography
(FAU)	Facial Action Unit
(GPS)	Global Positioning System
(HRV)	Heart Rate Variability
(HVAC)	Heating, Ventilation, and Air Conditioning
(OCC)	Occupant-Centric Control
(OTV)	Observed Thermal Vote
(PIR)	Passive Infrared
(PMV)	Predicted Mean Vote
(RH)	Relative Humidity
(ST)	Skin Temperature
(VR)	Virtual Reality

CHAPTER 1: INTRODUCTION

This chapter introduces the research focus, highlighting the importance of occupant comfort in indoor environments. It presents the background and motivation for the study, outlines the research objectives, describes the research approach, and summarizes the key contributions of this work.

1.1 Background and Motivation

Occupants spend approximately 90% of their time indoors, where environmental conditions significantly influence their comfort, health, and productivity (Balaji et al. 2018). Comfort in indoor spaces is influenced by dynamic environmental stimuli such as temperature, lighting, and air quality, as well as personal and social interactions with the surroundings (Ganesh et al. 2021). Ensuring an optimal indoor environment is particularly challenging due to the variability in occupant behavior and differences in environmental preferences (Kim, Schiavon, and Brager 2018).

Despite advancements in thermal comfort research, a key challenge remains in understanding how comfort perception varies across different climatic and cultural contexts. Most studies have been conducted in the Global North (Stazi, Naspi, and D'Orazio 2017), limiting their generalizability to other climatic and cultural contexts. Understanding how thermal comfort perceptions vary across different geographic regions is crucial for developing more inclusive and adaptable comfort models (Luo et al. 2018). This thesis addresses these concerns by investigating location-specific influences on comfort perception, comparing subjective and physiological responses to thermal conditions across different climatic zones.

At the same time, accurately assessing comfort requires an understanding of the level of detail necessary for reliable monitoring. While thermal comfort has traditionally been evaluated using self-reported surveys or environmental sensors, recent studies highlight the role of physiological responses in shaping comfort perception. Advanced monitoring techniques, such as ST, HRV, and EEG, offer deeper insights but vary in complexity and intrusiveness. This raises an important question: Do detailed physiological measurements provide significant advantages in assessing thermal comfort, or can non-invasive techniques, such as infrared imaging, serve as effective alternatives?

Beyond thermal comfort, cross-modal effects between lighting and thermal perception have gained increasing attention in recent research. One such area of interest is the hue-heat hypothesis (HHH) (Mogensen and Horace 1926; Tsushima et al. 2020), which suggests that artificial lighting characteristics (such as color temperature) influence occupants' thermal perception. However, many comfort models do not account for these interactions, and experimental results have been inconsistent due to differences in methodology and location-specific conditions (Zhao and Li 2023; Mamulova et al. 2023). Investigating the extent to which lighting variations influence thermal perception can inform the development of more integrated comfort assessment and control strategies.

1.2 Research objectives

The primary aim of this thesis is to establish a foundational understanding for OCC by investigating the level of detail required to characterize occupant comfort and performance in indoor environments. These objectives are designed to integrate data collection methods, multi-domain comfort assessment, and the physiological and performance impacts of thermal conditions. The key objectives of this research are outlined as follows:

1. **Review of Data Collection Methods for OCC:** This section of the thesis aims to review and analyze the data collection methods employed in OCC strategies, which are essential for optimizing building operations based on occupant behavior and preferences. Various sensing and acquisition approaches were examined, including physiological measurements, occupants’ interactions with building systems (e.g., thermostat adjustments, light switches) and environmental parameters (e.g., temperature, humidity, and CO_2 levels). The goal is to identify existing research gaps and provide a comprehensive overview of how occupant data can be gathered and applied to improve both energy efficiency and comfort in buildings.

2. **Analyzing the Impact of Thermal Conditions on Occupants’ Thermal Comfort, Performance and Physiological Responses in Office Environments:** This section examines how different thermal conditions (Cold, Neutral, Hot) influence occupants’ thermal comfort and physiological responses, as well as their cognitive performance in office environments. By measuring ST, HRV, and EEG data from

participants, the study analyzed associations between physiological signals and thermal comfort. Additionally, the study investigated how thermal conditions affect occupants' task performance, focusing on the participants' ability to maintain a "focused" cognitive state during tasks, as captured through EEG signals, and performance metrics such as task completion. Special attention was given to gender-responsive and location-based differences in physiological and perceptual responses.

3. **Assessing the Level of Detail Required for Thermal Comfort Evaluation:** This objective investigates the feasibility and accuracy of different comfort assessment methods, focusing on the trade-offs between detailed physiological monitoring and less intrusive techniques such as infrared imaging. By analyzing physiological data (e.g., skin temperature, heart rate variability, and EEG), this research evaluates whether complex physiological measurements provide substantial advantages over more practical, non-contact methods for comfort assessment.

4. **Examining the Impact of Lighting Conditions on Occupants' Thermal Comfort in Different Climatic Zones:** This objective extends the research scope by evaluating how lighting conditions, specifically varying Correlated Color Temperature (CCT), influence thermal comfort. This international inter-laboratory experiment investigates the HHH and cross-modal interactions between lighting and thermal comfort. The findings contribute to a deeper understanding of how lighting can be integrated into OCC strategies to enhance adaptive indoor climate control.

Through these objectives, this thesis seeks to enhance OCC strategies by improving the characterization of thermal comfort and advancing the understanding of how lighting impacts thermal perception, which can inform future control strategies. The insights from this research provide recommendations for optimizing occupant comfort while promoting energy-efficient building operations.

1.3 Research Approach and Contributions

To address these objectives, this research is based on an international experimental study conducted across two distinct climate zones—Montreal, Canada (ASHRAE Climate Zone 6) and

Cairo, Egypt (ASHRAE Climate Zone 2B). The study evaluates thermal and visual comfort interactions under different temperature and lighting conditions, examining both subjective comfort responses and physiological data (EEG, HRV, and ST).

The experimental setup includes controlled office environments where participants are exposed to varied thermal and lighting conditions, allowing for a systematic comparison of comfort perceptions and physiological reactions. Additionally, this study compares high-detail physiological monitoring with less intrusive methods, addressing the broader question of how different measurement approaches impact comfort assessment accuracy and feasibility.

This thesis makes the following contributions to the field of occupant comfort research:

- It provides an in-depth analysis of sensing and data collection methods for occupant comfort assessment, detailing experimental setups, technologies, and physiological measurements used.
- It provides new empirical evidence on climate-specific and gender-responsive variations in occupant comfort perceptions, contributing to more inclusive and adaptive comfort models.
- It evaluates the trade-offs between high-detail physiological monitoring and non-invasive comfort assessment techniques, informing future advancements in occupant comfort evaluation methods.
- It examines cross-modal effects between thermal and visual comfort, testing the HHH across different climatic zones to determine its potential impact on thermal perception.

By addressing these aspects, this research aims to enhance our understanding of how environmental conditions shape occupant experiences and inform more effective comfort assessment strategies for diverse indoor environments.

Figure 1 presents a visual summary of the research flow, from conceptual framing to experimental design and resulting contributions.

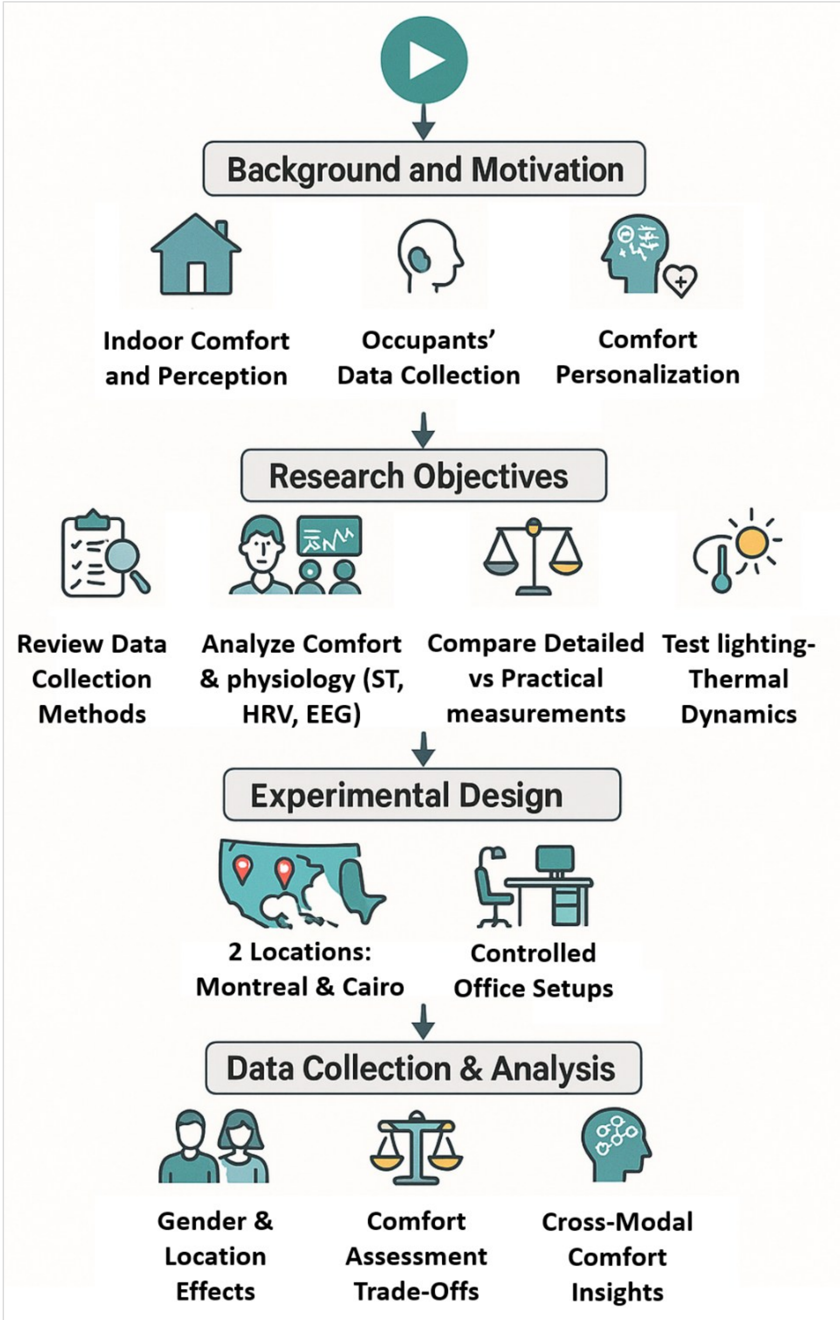

Figure 1. The key components of this thesis

1.4 Thesis organization

This thesis is structured into five chapters, each addressing key aspects of OCC strategies, thermal and visual comfort, physiological responses, and performance in office environments. The chapters are organized as follows:

Chapter1: Introduction

This chapter provides an overview of the research background and objectives, highlighting the importance of occupant comfort in indoor environments, particularly in office settings. The chapter introduces key concepts such as OCC, physiological monitoring, and the interplay between thermal and visual comfort, setting the stage for the study's focus on both perceptual and physiological responses to environmental stimuli.

Chapter 2: Literature Review and Data Collection Methods

This chapter provides a comprehensive review of existing research on occupant comfort, focusing on thermal and visual comfort, physiological data collection methods, and the role of OCC systems. It examines the limitations of previous studies, particularly their focus on the Global North, and highlights the need for location-specific and gender-sensitive approaches to comfort analysis. Additionally, it discusses the integration of multiple environmental domains and the use of wearable sensing technologies in monitoring occupant comfort.

In addition to reviewing the literature, this section explores sensing and data collection methods employed in occupant comfort research. It describes the experimental setups, equipment, and technologies used to gather physiological data, such as ST, HRV, and EEG-driven cognitive focus. Emphasis is placed on selecting appropriate sensors, measurement techniques, and study protocols to ensure reliable and meaningful data collection in diverse climatic contexts.

Chapter 3: The dynamics of Thermal Perception, Physiological Responses, and Performance in Office Environments

This chapter explores the relationship between thermal conditions, physiological responses, and cognitive task performance. The study analyzes how cold, neutral, and hot thermal environments impact both comfort perceptions and physiological metrics such as HRV and ST. Additionally, it examines the effects of thermal stress on cognitive performance, focusing on gender and location-specific differences. The findings provide insights into the practical implications of personalized indoor climate control.

Chapter 4: A Comparative Study of Thermal and Visual Comfort in Cold and Hot Climates

This chapter investigates the influence of lighting conditions and thermal environments on occupant comfort, examining both perceptual and physiological responses to varied indoor climates. The chapter focuses on gender-specific and location-based differences in comfort perception and physiological adaptation, and how these factors interact to shape overall comfort.

Chapter 5: Conclusion and Future Work

The final chapter summarizes the key findings of the research, emphasizing the importance of integrating thermal and visual comfort into building control systems. The chapter also discusses the implications of the study for designing adaptive, occupant-centric indoor environments and offers recommendations for future research, particularly the need for broader geographic and demographic studies.

CHAPTER 2: LITERATURE REVIEW AND DATA COLLECTION METHODS

Understanding occupant comfort is essential for designing energy-efficient and adaptive indoor environments. Research has shifted from static comfort models to occupant-centric approaches that integrate environmental, behavioral, and physiological factors. This chapter reviews key literature on thermal and visual comfort, physiological monitoring, and OCC strategies. It also highlights gaps in geographic and demographic diversity and explores emerging trends in comfort assessment, paving the way for more inclusive and adaptive models.

2.1 The Importance of Occupant Comfort in Building Design

Occupant comfort is increasingly recognized as a critical element in building design and operation. Occupants spend most of their time indoors, whether in residential, commercial, or office environments, making their interaction with the indoor environment crucial to their overall well-being and productivity (Balaji et al., 2018). Numerous studies have highlighted that building systems must balance energy efficiency with the goal of maintaining comfortable indoor conditions for occupants (Kim, Schiavon, & Brager, 2018). While the primary focus has traditionally been on achieving operational efficiency, recent advancements emphasize a more occupant-centric approach, where individual preferences, behaviors, and comfort play a pivotal role in optimizing building environments.

Ensuring thermal and visual comfort in buildings requires a delicate balance between environmental conditions and individual preferences. The challenge lies in the variability of occupant behavior, where individuals may respond differently to the same indoor environment. Factors such as temperature, humidity, lighting, and air quality all contribute to comfort perception, and their effects can be influenced by personal and cultural differences (Humphreys & Nicol, 2018).

2.1.1 OCC and Its Role in Adaptive Comfort Control

One of the emerging concepts in occupant comfort research is OCC. It represents a dynamic approach to building management, utilizing real-time data on occupant presence, behavior, and preferences to tailor building systems—such as heating, ventilation, and lighting—more effectively. Unlike traditional systems that operate on preset schedules or general assumptions, OCC systems are designed to adapt to the occupants' changing needs, thus providing services only when and where they are needed (Peng, Nagy, & Schlüter, 2019).

The growing implementation of sensing infrastructure has made OCC a viable solution for enhancing both energy efficiency and comfort. This is particularly important in modern office spaces where fluctuations in occupancy and personal comfort needs can result in inefficient energy use. By leveraging sensor data, OCC systems can respond dynamically to changes in indoor climate preferences, such as adjusting temperatures when occupants report discomfort or when sensors detect changes in environmental conditions.

However, challenges remain in understanding the complex nature of occupant behavior and comfort needs. Occupants' actions—such as adjusting thermostats, opening windows, and turning lights on or off—are often unpredictable and influenced by multiple factors including personal preferences, climate, and cultural background. This unpredictability complicates the development of accurate occupant models for building control systems. Research by Ouf, O'Brien, and Gunay (2019) highlights how assumptions about occupant behavior can lead to inefficient operations, such as heating or cooling unoccupied spaces or providing excessive ventilation. Addressing these issues requires a more robust understanding of occupant preferences, which can vary significantly depending on location-specific factors and cultural differences.

A key obstacle in refining OCC systems is the ability to collect reliable data that captures this behavioral variability. Effective models rely on real-time monitoring of occupant preferences, behaviors, and interactions with building systems, yet this requires an infrastructure capable of integrating environmental parameters—such as temperature, humidity, and lighting—with behavioral responses like thermostat adjustments or window operations. The challenge is further compounded by the fact that much of the existing research has been conducted in Europe and North America, focusing on relatively homogenous groups of occupants. This limits the applicability of findings to other climatic and cultural contexts, highlighting the need for more inclusive datasets that reflect diverse comfort expectations and behaviors (Luo et al., 2018).

Recent advancements in sensing technology have enabled researchers to explore novel approaches to data collection. These include the use of wearable sensors, which monitor physiological data such as heart rate, skin temperature, and brain activity, to gain deeper insights into how occupants respond to their environment (Ghahramani, Castro, et al., 2018). This shift towards non-invasive physiological monitoring offers a more granular understanding of comfort, moving beyond traditional surveys and subjective reports to objective, continuous data collection.

A comprehensive understanding of comfort requires integrating physiological responses with environmental and behavioral data. Comfort in indoor environments is influenced by a range of environmental factors, including thermal conditions (temperature, humidity, air velocity) and visual conditions (lighting quality, glare, color temperature). To optimize both energy use and occupant comfort, building systems must account for these variables and their interactions. Figure 2 illustrates the integration of occupant feedback, environmental monitoring, and adaptive control mechanisms in a comfort-responsive OCC system, enabling real-time adjustments to indoor conditions (ASHRAE, 2019).

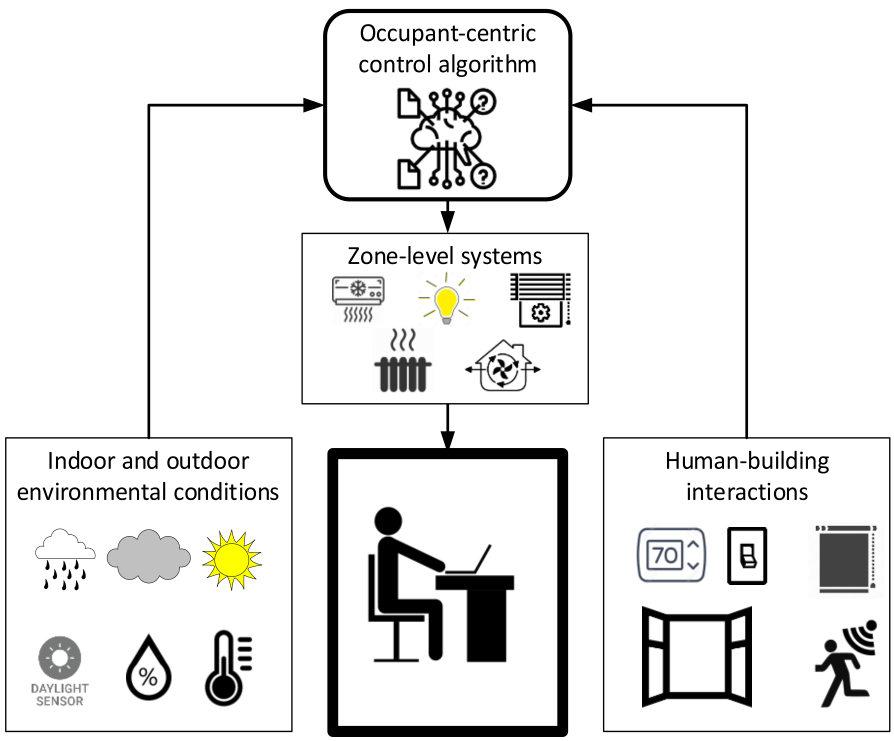

Figure 2 Overview of comfort-responsive OCC approach

Research has shown that occupants are highly sensitive to changes in both thermal and visual conditions. Kim, Schiavon, and Brager (2018) noted that even slight variations in temperature or lighting quality can lead to adjustments in occupant behavior, such as changing thermostat settings or moving to a different part of the room. This behavioral variability underscores the importance of real-time data collection to ensure building systems respond promptly and accurately to occupant needs.

2.2 Physiological Monitoring in Comfort Research

Traditional comfort assessment methods have relied on thermal sensation votes (TSV) and subjective surveys, which can introduce recall bias and variability (Fanger, 1970; Höppe, 2002). Recent advancements in wearable physiological sensors provide a more objective, continuous method for understanding occupant comfort responses (Pigliautile et al., 2023).

These technologies track real-time biometric responses that provide valuable insights into occupant comfort. ST reflects localized thermal changes due to environmental exposure, offering a direct physiological indicator of thermal discomfort (Ghahramani, Castro, et al., 2018). HRV serves as a measure of stress levels and physiological adaptation to discomfort, helping researchers assess how the body responds to fluctuating environmental conditions (Chang et al., 2019). Additionally, EEG is used to evaluate cognitive states such as focus, fatigue, and relaxation, providing insights into the mental impact of thermal and visual conditions in indoor environments (Alimohammadi et al., 2018).

While these wearable sensors offer significant advantages, challenges remain in ensuring data accuracy, privacy, and scalability (Alfano et al., 2021). Additionally, physiological data can be influenced by factors beyond environmental discomfort, such as emotional state, cognitive load, and health conditions (Lan et al., 2010).

2.3 The Interaction Between Thermal and Visual Comfort

The growing interest in a multi-domain approach to comfort research highlights the interconnected nature of thermal and visual comfort. Studies have shown that both thermal and visual comfort can influence occupant well-being and productivity, particularly in office environments. For example, poor lighting conditions can exacerbate thermal discomfort, while an overly bright or dim environment can lead to fatigue and decreased productivity (Zhao & Li, 2023).

The hue-heat hypothesis (Meryl et al., 1926; Song et al., 2016), which suggests that different lighting colors can affect thermal perception, has gained renewed interest in recent years. Research has demonstrated that lighting with a higher CCT is often associated with cooler thermal perceptions, while warmer lighting is perceived as more comfortable in colder conditions (Zhai et al., 2021). This relationship between lighting and thermal perception is a key factor in designing occupant-centric spaces that balance multiple comfort domains.

This cross-modal interaction between lighting and temperature offers new insights into enhancing indoor comfort and well-being. Adjustments in lighting conditions can influence thermal perception, potentially reducing the need for extensive climate control interventions to maintain a comfortable environment (Mamulova et al., 2023). However, most existing studies have focused on temperate regions, and further research is necessary to explore these effects across diverse climatic and cultural contexts (de Dear et al., 2013). The complex interplay between thermal and visual comfort highlights the need for more precise and adaptive approaches to occupant-centric building management. While research has demonstrated that lighting conditions influence thermal perception and overall comfort, understanding these relationships requires extensive data collection across diverse occupant groups and environmental contexts. Differences in climate, cultural expectations, and individual physiological responses contribute to variations in how occupants experience and regulate their indoor environments.

To develop OCC systems that effectively respond to these factors, robust data collection frameworks are necessary. Monitoring real-time occupant interactions with building systems—such as temperature adjustments, lighting preferences, and physiological responses—enables the development of adaptive models that optimize comfort while maintaining energy efficiency. The next section explores emerging trends in data collection for OCC, detailing the methodologies used to capture occupant behavior, environmental conditions, and physiological indicators that inform adaptive comfort control.

2.4 Data Collection and Trends in OCC

OCC systems play a pivotal role in balancing energy efficiency and occupant comfort by acquiring real-time data on occupants' behaviors, preferences, and environmental conditions. The effectiveness of OCC depends on accurate data collection methods, which require a combination of sensor-based monitoring, behavioral tracking, and physiological assessments. Understanding how data is gathered, processed, and applied in OCC frameworks is essential for developing more adaptive and responsive building systems.

To build a comprehensive understanding of sensing and data collection methods, a systematic literature review was conducted, focusing on keywords such as "Occupant-centric control," "Occupants' data," "Occupants' sensing," "Occupants' behavior," and "Occupants' preferences." General databases like Google Scholar and ScienceDirect, as well as domain-specific journals, were utilized. After filtering out studies that did not specifically address OCC-related data collection and sensing approaches, a total of 87 publications were selected for detailed analysis.

The bibliographical analysis of the selected studies revealed key trends in OCC research, particularly regarding publication timelines, building types, and monitoring durations. As shown in Table 1, approximately 70% of the reviewed papers were published within the last four years (2020-present), reflecting the growing interest in OCC research and its increasing relevance in the field.

Table 1 Bibliographical information of the analyzed papers

Year of publication	**Percentage of papers (%)**	**Building type**	**Percentage of papers (%)**	**Monitored duration**	**percentage of papers (%)**
2020-2024	70.3	Office	55.6	Less than a week	20.2
2016-2020	18.85	Academic	16.7	1 month	9.8
2012-2016	6.75	Residential	11.1	2 months	41
Before 2012	4.1	Commercial/Other	16.6	More than 2 months	29

A keyword occurrence analysis was also performed using a text-mining tool to determine the most used terms in OCC-related publications. The results (depicted in Figure 3) showed that terms like "occupant," "data," and "collection" had the highest occurrence, indicating the strong focus on data acquisition in this field. High occurrences of words such as "adaptive," "intelligent," and "learning" further suggest that the research trend is increasingly oriented toward automation and the digitalization of data collection processes.

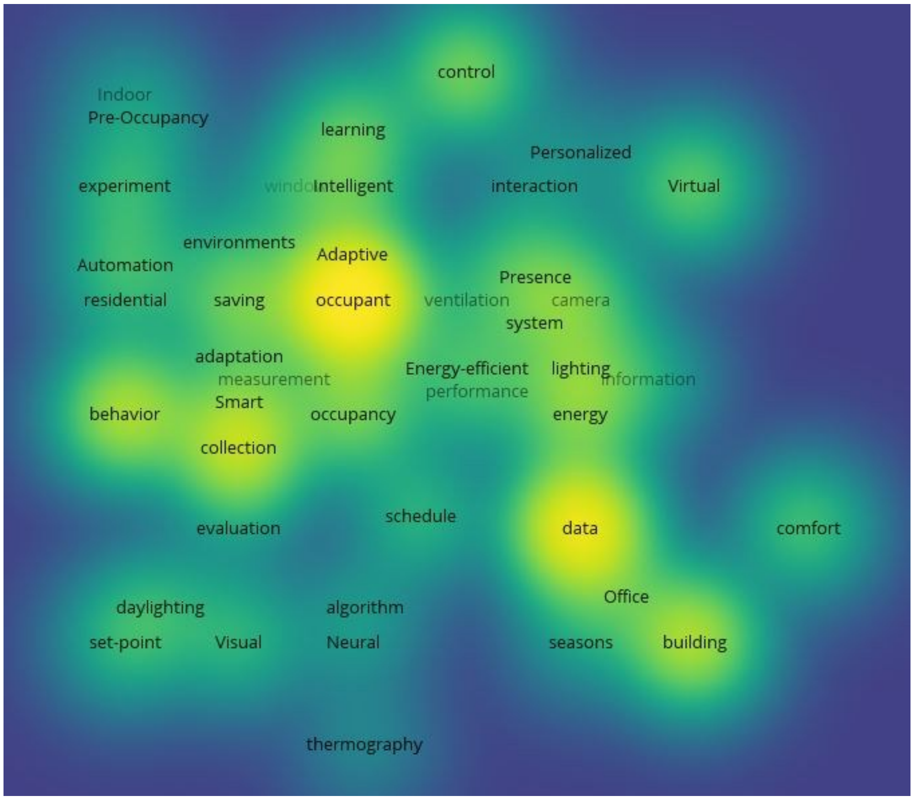

Figure 3 occurrence of keywords

2.5 Identification of Data Collection Approaches

The success of OCC is directly linked to the accuracy and timeliness of the data collected about occupants' behaviors, preferences, and interactions with the built environment. These systems rely on extensive data regarding the indoor and outdoor environmental conditions, occupant preferences, and real-time interactions with building systems. In this section, we will explore the different approaches and methods used to gather these critical data for OCC, the technologies involved, and how these data influence occupant comfort and energy efficiency in buildings.

2.5.1 Overview of Data Collection in OCC

To develop effective OCCs, data collection must encompass multiple facets of the built environment and the way occupants interact with it. These can be broadly categorized into three primary areas:

- **Occupants' interactions with building systems**: Includes how individuals interact with HVAC systems, lighting, windows, etc.

- **Indoor/outdoor environmental conditions**: Factors like temperature, humidity, CO_2 levels, and more, that may trigger occupant actions.
- **Occupant preferences and physiological responses**: Collecting data on individual comfort levels, demographic information, and physiological indicators helps in personalizing building operations to enhance comfort.

The figure below demonstrates an overview of the data collection requirements and methods, categorized by the different types of information needed and the tools used to gather that information.

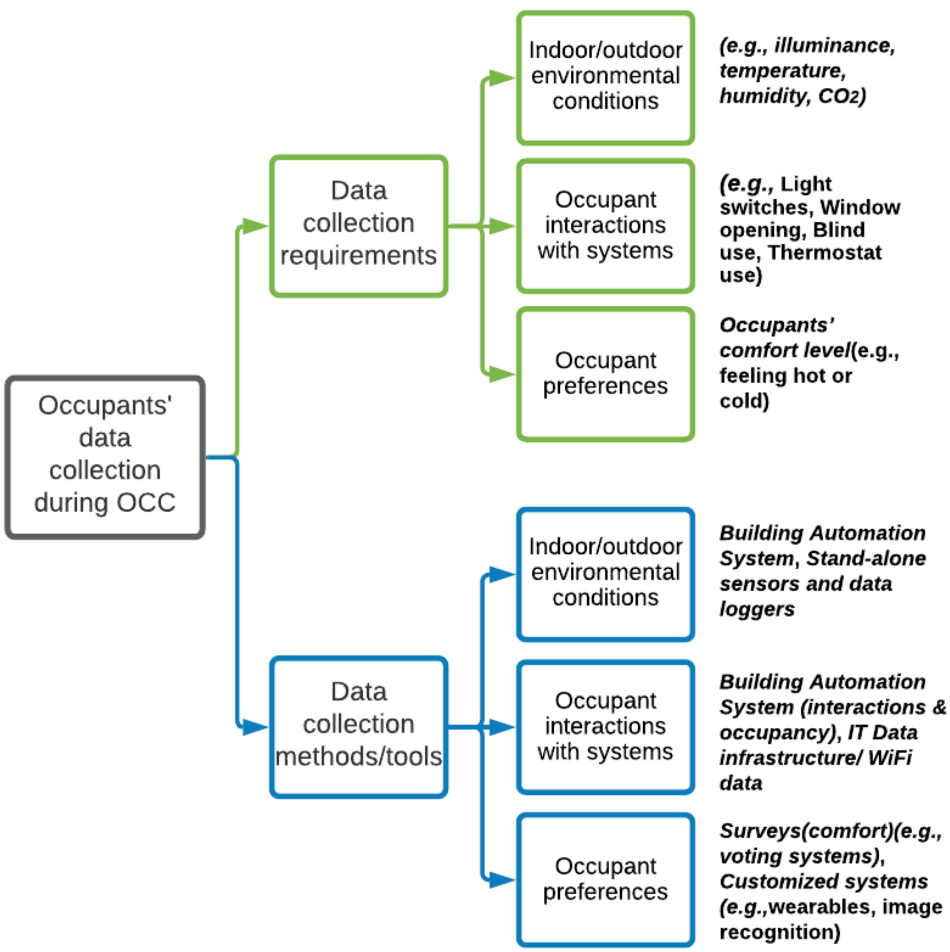

Figure 4 Occupants' data collection during OCC

Figure 4 outlines the relationship between data collection requirements (green) and the methods/tools used to capture this data (blue). These processes form the backbone of OCC systems and ensure that both real-time actions and long-term trends are accurately captured to optimize building performance.

2.5.2 Data Collection Requirements

The data collected for OCC systems must provide insight into how occupants interact with their environment, how external factors influence these interactions, and how preferences can vary across individuals or groups. Table 2 below provides an overview of the different types of data required for OCC systems.

Table 2 Categories of data collection requirements

Data type	Description	Example
Indoor/outdoor environment	Triggers of occupant interactions	Indoor/outdoor temperature Illuminance Relative Humidity (RH) Sounds/noises Air velocity/circulation Solar radiation Smell visual view
Occupants' interactions	Action	Occupancy Thermostat adjustment Window status (on/off/stage) Blind status (on/off/stage) Door status (on/off) Lighting status (on/off/dim) Ceiling fan status (on/off/stage)

			Portable heater status (on/off/stage) Computer status (on/off)
Occupants' Information	Occupant demographic and contextual information	Attributes	Gender Age range Country
		Attitudes	Comfort preference (thermal/IAQ/visual) Energy use style
		Proxy	Wi-fi APs CO2 concentration
	Occupants' physiological information		Facial recognition/image recognition Emotions Heart rate/skin temperature/vascular analysis
Other	Occupancy		Presence/status Count Location

As illustrated by studies like Gunay et al. (2015) and Park & Nagy (2020), real-time data on environmental conditions and occupant actions—such as window openings or thermostat adjustments—play a key role in optimizing building systems. Furthermore, understanding occupant preferences and physiological responses allows OCC systems to tailor the environment to meet individual comfort levels, enhancing the overall indoor experience while conserving energy.

2.5.3 Data Collection Methods and Tools

To collect the data required for OCC systems, several tools and methods have been developed. Two primary sources of data include: Building Automation Systems (BAS) and standalone sensors. While BAS are common in modern buildings and can collect real-time data on temperature, humidity, and system operations, standalone sensors are often deployed to capture specific interactions and supplement data in buildings that may lack advanced BAS infrastructure. Table 3 provides a summary of the common methods used for occupant detection and interaction monitoring.

Table 3 Methods for occupancy detection interaction monitoring

Method	**Example**
Motion sensor	PIR (Dodier et al. 2006; Duarte, Van Den Wymelenberg, and Rieger 2013) Lighting switch sensor (Chang and Hong 2013) Pressure sensor (Labeodan et al. 2015; 2016) Ultrasonic sensor (Shih 2014)
Vision-based technology	Camera (Benezeth et al. 2011) image-processing occupancy sensor (Brackney et al. 2012)
RF-based technology	RFID (Li, Calis, and Becerik-Gerber 2012) Bluetooth (Harris and Cahill, n.d.; Conte et al. 2014) Wi-Fi (Conte et al. 2014; Balaji et al. 2013)
Virtual sensors	PIR, pressure, and keyboard and mouse sensors, GPS location and Wi-Fi connection from Wi-Fi hotspots (Chen and Ahn 2014; Y. Zhao et al. 2015)
	Wi-Fi and BLE (Jin, Jia, and Spanos 2017) CO2 magnetic reed switches, and PIR sensors (Mashuk et al. 2018)

	IMU, Wi-Fi, humidity, and illuminance sensors (Javed et al. 2017)
	Keyboard and mouse activity, webcam, microphone, PIR, temperature, RH, light, proximity sensors, and pressure mat (Z. Zhao et al. 2017)
Multi-sensor networks	Smart Door (LDR and ultrasonic Sensors) (Newsham et al. 2017)
	Contact closure, PIR, and CO2 sensors (Nesa and Banerjee 2017)
	PIR, pressure, and acoustic sensors (Newsham and Birt 2010)
	PIR, CO2, RH, temperature, air velocity and globe thermometer (Nguyen and Aiello 2012)

Motion sensors (e.g., PIR) are widely used for detecting occupant presence and activity, while more advanced technologies like vision-based or RF-based systems offer capabilities for tracking and identifying occupants in real-time (Benezeth et al., 2011; Li et al., 2012). Multi-sensor networks, which incorporate a combination of temperature, CO2, pressure, and other sensor types, are particularly useful for developing a comprehensive understanding of occupancy patterns and building interactions.

Additionally, directly collecting data on occupant preferences is another method used in OCC. This has traditionally been achieved through manually administered comfort surveys (Brager et al., 2004; Karjalainen, 2007). However, recent advancements have introduced mobile applications and wearable devices that allow continuous data collection. Figure 5 below shows an example of how Jayathissa et al. (2020) used a mobile application and wearables like Fitbit smartwatch to gather thermal, visual, and aural feedback from occupants in real-time.

Figure 5 Collection of occupants' data using surveys integrated into apps (Jayathissa et al. 2020)

The figure illustrates the feedback mechanism, starting from the home screen, allowing occupants to provide real-time thermal, visual, and aural comfort preferences. This data is directly integrated into building control systems to adjust indoor conditions dynamically. Other wearable sensors, like the Oura Ring, provide an unobtrusive way to capture physiological data, including heart rate and skin temperature, allowing for real-time adjustments to the indoor environment without requiring manual input from occupants.

2.5.4 Experimental Setups and Emerging Approaches

Recent advancements in sensor technology and data acquisition methods have enabled researchers to explore novel ways of gathering occupant-centric data. These include the use of wearables, facial recognition systems, and virtual reality environments, each offering unique advantages for data collection in OCC research.

- Wearables: Devices like the smartwatches and Oura Ring allow for continuous, non-invasive monitoring of physiological data such as heart rate, skin temperature, and sleep quality (Ghahramani et al., 2018). These devices offer a less intrusive means of capturing real-time physiological data without significantly disrupting daily routines.

- Facial Action Units (FAU): FAUs, combined with technologies like OpenFace, enable real-time analysis of facial muscle movements to detect emotions such as discomfort or satisfaction. This approach has been employed to create dynamic building systems that adjust environmental conditions based on occupant feedback (Allen & Overend, 2019). Figure 6 demonstrates the FAU-based data collection process, which involves video analysis of occupant facial expressions to infer comfort levels.

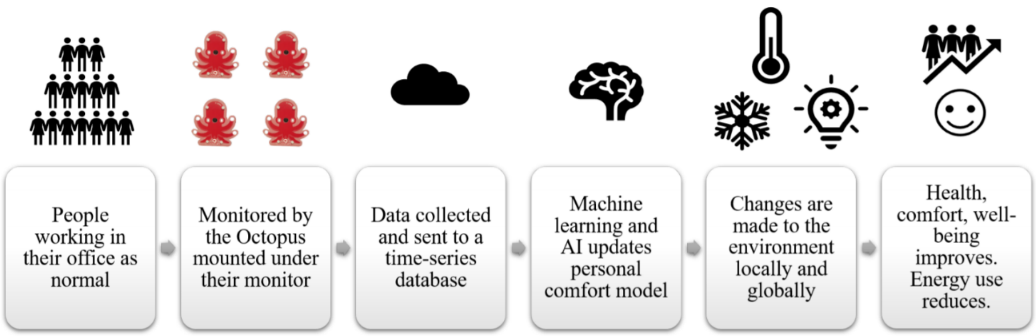

Figure 6 Facial Action Unit (FAU) data collection method (Allen and Overend 2019)

- Virtual and Augmented Reality (VR/AR): VR allows researchers to simulate and control building environments, providing a platform to observe how occupants interact with building systems under controlled conditions (Kim, Schiavon, & Brager, 2018). VR/AR environments are increasingly used to test occupant responses to lighting or temperature changes, offering a cost-effective alternative to large-scale, real-world studies. Figure 7 illustrates how VR environments can be used to model lighting or temperature changes and analyze the impact on occupant comfort without the constraints of physical spaces.

Figure 7 Use of VR in OCC research (Heydarian and Becerik-Gerber 2017)

2.5.5 Experimental Setups and Challenges

OCC research often utilizes experimental or mock-up environments to study occupant comfort and building interactions. In these controlled settings, participants are exposed to different environmental conditions (e.g., temperature, lighting) while their physiological responses and behaviors are monitored. This allows researchers to collect high-quality data on a range of comfort metrics.

For example, experimental setups using wearables, cameras, and sensors can capture data on skin temperature, vascular responses, and facial expressions—key indicators of thermal and visual comfort—and provide opportunities for detailed analysis in controlled mock-up environments.

2.6 Research Gaps and Future Directions

Despite progress in OCC and physiological comfort research, several challenges remain that must be addressed to develop more inclusive and adaptive occupant-centric models.

One significant limitation is the geographic concentration of studies. Most of the research on occupant comfort has been conducted in Europe and North America, limiting the generalizability of findings to other climatic and cultural contexts (Luo et al., 2018). Expanding studies to diverse geographic regions is necessary to ensure that comfort models accurately reflect global occupant preferences.

Additionally, there is a lack of integrated models that account for thermal and visual comfort interactions. The relationship between lighting conditions and temperature perception remains an emerging field, with limited real-world applications (Zhao & Li, 2023). Investigating these cross-modal effects further could lead to more energy-efficient building strategies, optimizing comfort while reducing operational costs.

Advancements in physiological monitoring have introduced new methods for assessing comfort, such as wearable sensors and biometric tracking. However, standardized frameworks for integrating physiological data into OCC models are still lacking (Pigliautile et al., 2023). Developing scalable, non-intrusive, and privacy-conscious data collection techniques will be critical to refining real-time occupant comfort assessments.

Another key challenge is the variability in comfort perception by location and gender. Studies indicate that occupants in different climates may have distinct thermal expectations, while gender-specific preferences further complicate the development of universal comfort models (Indraganti, 2010). Addressing these demographic and environmental variations will require personalized climate control strategies that can adapt dynamically to individual needs.

Future research should focus on enhancing sensing and data collection techniques to support real-time adaptive indoor environments. Additionally, long-term monitoring strategies and standardized evaluation methods help refine OCC frameworks, ensuring that they are robust, practical, and capable of balancing energy efficiency with occupant well-being.

The continued advancement of physiological sensing technologies, emotional feedback systems, and environmental monitoring tools will further facilitate the integration of real-time occupant comfort data into building control systems. By addressing these research gaps, future OCC implementations can create adaptive, personalized indoor environments that optimize comfort while promoting sustainability.

CHAPTER 3: *THE DYNAMICS OF THERMAL PERCEPTION, PHYSIOLOGICAL RESPONSES, AND PERFORMANCE IN OFFICE ENVIRONMENTS*

This chapter explores how thermal conditions affect physiological responses and task performance in office environments. By examining regional and gender-based differences, the study provides insights into adaptive climate control and its impact on occupant comfort and productivity.

3.1 Introduction

This chapter examines the relationship between thermal conditions, physiological responses, and task performance in office environments. Specifically, it delves into the interplay of thermal perception—how individuals perceive their environment in cold, neutral, and hot conditions—and the physiological measurements obtained from ST, HRV, and cognitive states as determined by EEG data. The chapter also evaluates how thermal conditions impact cognitive task performance, with a particular focus on how gender and geographical location influence these dynamics.

The two central test locations for this study, Montreal, Canada (representing a cold climate - Dfb, ASHRAE climate zone 6A), and Cairo, Egypt (representing a hot climate - BWh, ASHRAE climate zone 1B), offer a robust comparative framework for understanding location-based disparities in thermal comfort and performance. The study employs an experimental protocol that involves repeated exposure of participants to varying thermal environments, measuring both subjective thermal votes and objective physiological responses. Figure 8 presents the laboratory setups for the two test locations.

(a) (b)

Figure 8 laboratory setups in Montreal, Canada (a) and Cairo, Egypt (b).

The primary aim of this chapter is to analyze the relationship between thermal conditions and thermal votes, physiological measurements, and cognitive performance, and to identify how gender and location influence these relationships. The ultimate goal is to provide actionable insights that can inform the development of personalized, adaptive indoor environments that improve both comfort and performance.

3.2 Study Design and Experimental Protocol

This section outlines the experimental methodology, including the study design, participant recruitment, data collection methods, and the experimental conditions to which participants were exposed.

3.2.1 Study Design and Participant Recruitment

The study involved 52 participants, including 29 females and 23 males, recruited from Concordia University, Montreal and AUC University, Cairo. Participants ranged in age from 19 to 45 years and were selected to represent a wide cross-section of office workers. Each participant was exposed to three different thermal conditions (i.e., cold, neutral, and hot).

The tests were conducted across two seasons—summer and winter—to account for seasonal variations in thermal perception and physiological responses. Participants were exposed to the following thermal conditions (table 4).

Table 4 Adopted thermal conditions.

Domain	Factors		Levels		
Thermal	Air temperature [°C]	Summer	21 (Cold)	24 (Neutral)	27 (Hot)
		Winter	18 (Cold)	21 (Neutral)	25 (Hot)
	Humidity [%]		Constant (45% +/- 10%)		

Each participant completed the test individually to prevent any potential interference with their environmental perception. The test lasted for 30 minutes (as shown in Figure 9) under consistent thermal conditions. To ensure thorough data collection, each participant underwent the test three times on different days (using a repeated measures design) to experience all three temperature conditions. These tests were spaced out by at least 24 hours (non-consecutive days) to allow for a washout period between sessions. The same protocol was applied during both the summer and winter seasons. The experiment consisted of three main stages:

- Test Explanation and Acclimatization:
  This 20-minute period allowed participants to adapt to the indoor temperature. During the first 5 minutes, participants were given an overview of the experimental procedure and asked to read an information sheet, sign a consent form, and complete a questionnaire detailing their personal characteristics and general preferences. This step was only completed during the first of the three experiments. During the acclimatization phase, wearable sensing devices for physiological monitoring (e.g., skin temperature and HRV sensors) were applied. The EEG device was placed towards the end of this period to minimize any discomfort for the participants.
- Recording Stage:
  This stage lasted 5 minutes, during which physiological data was collected. While being monitored, participants engaged in a cognitive task designed to maintain focus. The task was a logic game called "Brain Yoga - Logic," where participants had to identify the correct color and position of three balls. The number of successful plays and attempts were recorded during this phase.
- Questionnaire:

After the recording stage, participants completed a standard right-here-right-now thermal comfort questionnaire, which gathered real-time feedback on their perceived thermal conditions.

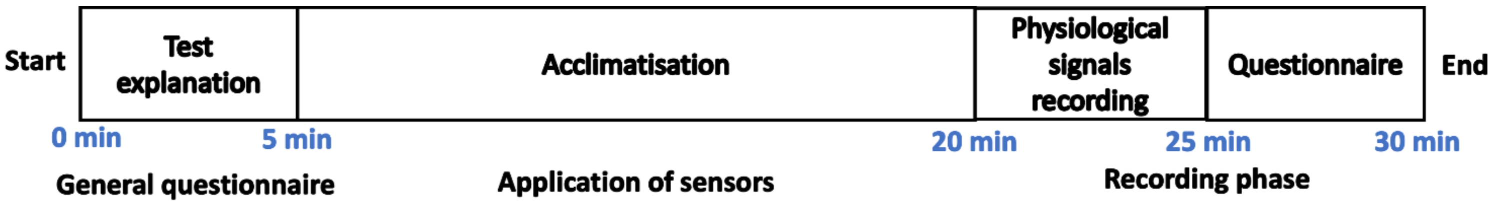

Figure 9 Experiment procedure

3.2.2 Environmental Control

Each experimental room was equipped with advanced climate control systems to precisely regulate the operative temperature, relative humidity, and air velocity. Both natural and artificial lighting were controlled to maintain consistent conditions across all participants and sessions. The test rooms were preconditioned for at least 2 hours before each session to ensure temperature and environmental parameters were stable.

The test rooms in Montreal and Cairo had slight differences in internal finishes and climate control systems, but care was taken to ensure that the operative temperature and environmental parameters were similar across both locations. The participants wore standardized clothing (0.5 clo in summer and 1 clo in winter), and their metabolic rate was kept low (58 W/m^2) to simulate typical sedentary office activities.

3.2.3 Physiological Monitoring

Participants' physiological data were collected using a range of wearable sensors and monitoring devices:

ST: Measured using both contact sensors (Oura ring, temperature probes) and contactless sensors (FLIR thermal cameras). Contact skin temperature was measured at the hand or wrist, while contactless temperature measurements were obtained from the forehead, cheek, nose and neck.

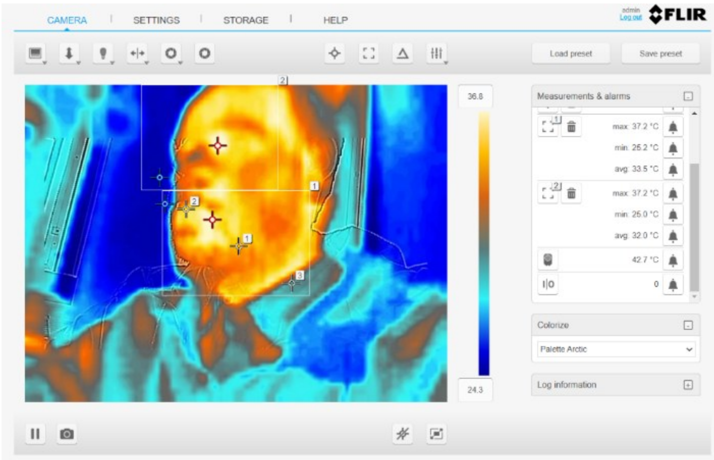

Figure 10 Thermal camera measuring hotter (forehead, neck) and colder (nose, cheek) facial regions.

HRV: Measured using the Fitbit Versa 2 smartwatch. HRV is a critical measure of physiological stress and the body's ability to adapt to environmental stimuli.

Figure 11 Oura ring generation 3 and Fit bit Versa 2 measuring ST and HRV

EEG-Driven Focus State: EEG signals were recorded using Emotiv Epoc^{X} headsets to track cognitive states, particularly the participant's ability to remain focused during tasks.

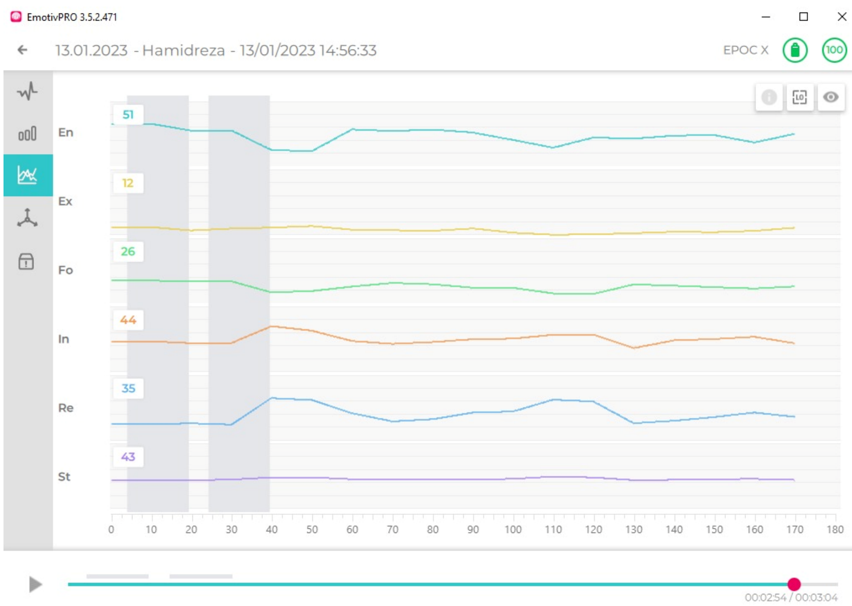

Figure 12 EEG signals capturing participants' emotional states

3.2.4 Task Performance and Data Collection

To evaluate cognitive performance under varying thermal conditions, participants engaged in the logic-based task "Brain Yoga," designed to challenge memory, attention, and problem-solving skills. During the task, participants attempted to position three colored marbles accurately, receiving immediate feedback after each attempt. A gold indicator signified both correct color and position, while a silver indicator indicated only the color was correct (Figure 13). The total number of completed rounds and attempts were recorded as objective performance metrics, providing a quantifiable measure of task engagement and cognitive focus. EEG data were also collected to assess participants' ability to maintain focus during the task. This task-based approach, previously used in cognitive performance research (e.g., [17,18]), offered a robust method for evaluating performance under different thermal conditions.

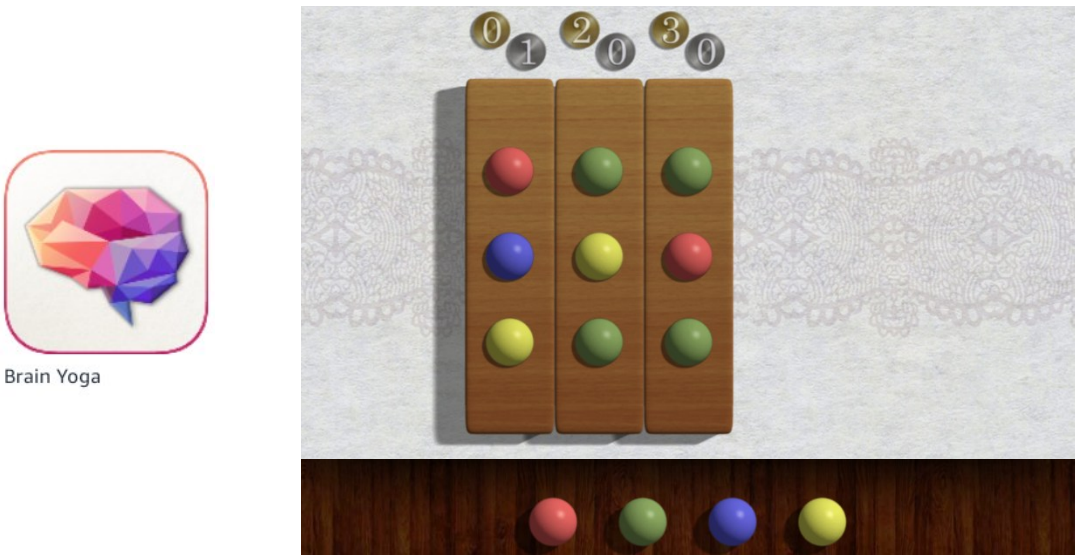

Figure 13 Game overview indicating participants' performance

Prior to testing, participants provided demographic data, including age, gender, height, and weight, along with self-rated thermal sensitivity on a scale. This information was collected once at the beginning of the study to establish baseline participant characteristics. In addition to physiological monitoring, participants also provided subjective feedback on their thermal comfort using a thermal comfort questionnaire, which is presented in the Appendix.

Table 5 presents an overview of the monitored parameters along with the corresponding equipment used for their measurement.

Table 5 Monitored parameters and equipment

Monitored Parameter	Equipment	
	Laboratory 1	**Laboratory 2**
Air Temperature	Omega TJ36-ICIN	Delta Ohm HD2001.1
Globe Temperature	Delta Ohm TP3276	Delta Ohm TP 875

Relative Humidity	Siemens Desigo (BMS)	Delta Ohm HD2001.1
Air Velocity	AP471S4 – Omni-Directional Hotwire Probe	Delta Ohm HD4V3TS4
Illuminance	Delta Ohm HD 2021T	Delta Ohm HD2021T
EEG	Emotiv-Epoc^x	Emotiv-Epoc^x
HRV	Fitbit Versa 2	Fitbit Versa 2
Contact ST	Oura ring	Temperature Probes
Contactless ST	FLIR AX8	FLIR AX8

3.2.5 Data Processing and Statistical Analysis

A comprehensive statistical analysis was conducted to examine the relationship between participants' reported thermal sensations and their physiological responses. Prior to applying ANOVA, the dataset was tested for normality and homogeneity of variance to confirm suitability for ANOVA analysis. The Shapiro-Wilk test showed that the data met the normality requirement for key variables ($p > 0.05$ for each physiological feature), and Levene's test confirmed the homogeneity of variance across groups ($p > 0.05$ for all comparisons).

Using repeated measures ANOVA, we compared the means of physiological features across thermal conditions (cold, neutral, hot) to identify statistically significant variations based on participants' thermal perceptions. Medians and averages were used to interpret the data further, focusing on central tendencies within each group. This approach provided a comprehensive assessment of physiological responses across different thermal environments.

For each of the following comparisons—thermal conditions, thermal votes, physiological measurements (including contact/contactless skin temperature, HRV), EEG-derived focused state, and task performance—data were analyzed across gender and location groups. Specific analyses included:

1. **Thermal Conditions and Thermal Votes:**

Participants' thermal votes were compared across the three thermal conditions to assess their association with physiological features (e.g., HRV, ST) and identify any significant differences.

2. **Physiological Measurements and Thermal Votes:**

Skin Temperature: Both contact (Oura ring or temperature probes) and contactless (thermal camera) skin temperature measurements were analyzed with ANOVA to assess variations across thermal conditions, gender, and location.

Heart Rate: Heart rate data from the Oura ring and Fitbit smartwatch were examined using ANOVA, comparing averages across thermal conditions and assessing variations by gender and location.

3. **Impact of Thermal Conditions on Performance:**

EEG-Derived Focused State: ANOVA was used to compare participants' focus levels, as determined by EEG signals, across all the thermal conditions. Gender and location differences were further analyzed.

Task Performance (Game Results): Task performance metrics in the "Brain Yoga" game, including the number of rounds completed and attempts, were analyzed with ANOVA to determine the influence of thermal conditions, with comparisons by gender and location.

3.3 Thermal Conditions and Thermal Votes

The first stage of analysis involved comparing participants' thermal votes with the actual thermal conditions they experienced. Thermal votes were collected using the 7-point PMV scale, which ranges from -3 (cold) to +3 (hot), with 0 representing neutral thermal sensation.

3.3.1 Overall Findings

Across both test locations, participants generally rated themselves as feeling warmer in the hot condition and cooler in the cold condition, as expected.

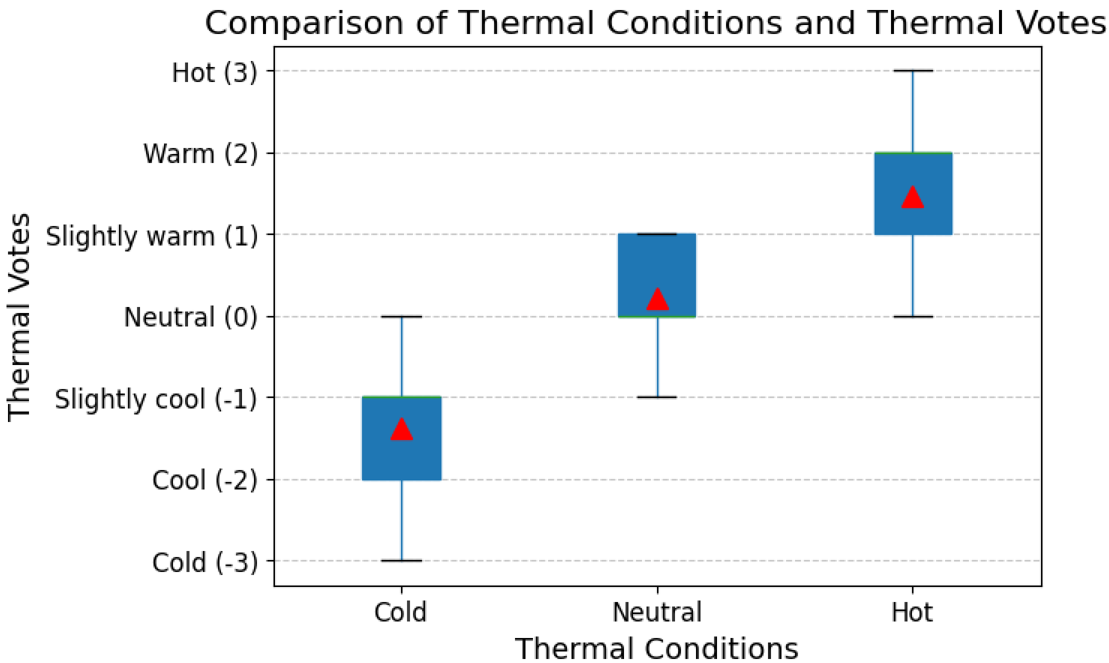

Figure 14 Comparison of thermal conditions and thermal votes

However, significant differences were observed in how male and female participants, as well as participants from different locations, rated their thermal comfort. The ANOVA results for thermal votes demonstrated significant differences across thermal conditions ($F = 210.73$ for males, $F = 278.50$ for females, $p < 0.001$). Participants consistently rated the cold condition as less comfortable than the neutral or hot conditions, although some individuals from Cairo reported higher tolerance for hot environments, as expected based on their acclimatization to warmer climates.

In Montreal, participants tended to perceive colder environments more favorably, with fewer extreme votes in the cold condition compared to participants from Cairo. This disparity suggests that local climate plays a role in shaping thermal tolerance, with individuals from cold climates better adapted to colder environments ($F = 269.48$ for Cairo, $F = 248.70$ for Montreal, $p < 0.001$).

3.3.2 Gender-Specific Findings

The analysis highlights significant variations across groups. For both male and female participants, ANOVA results confirm that thermal conditions had a statistically significant effect on thermal votes. Specifically, for males, the ANOVA test returned an F-value of 210.73 ($p < 0.0001$), while for females, the F-value was 278.50 ($p < 0.0001$). These values indicate that thermal conditions strongly influenced perceived thermal comfort across gender groups. The mean thermal votes for males were 1.5 (cold), 3.2 (neutral), and 5.8 (hot), while females reported means of 1.3 (cold), 3.1 (neutral), and 5.9 (hot), showing clear shifts in perceived comfort as thermal conditions varied.

Figure 15 presents a comparison of thermal votes by gender, displaying the mean and median values for males and females under each thermal condition. The data show a consistent pattern in how thermal environments influence perceived comfort, with clear differences in the magnitude of responses.

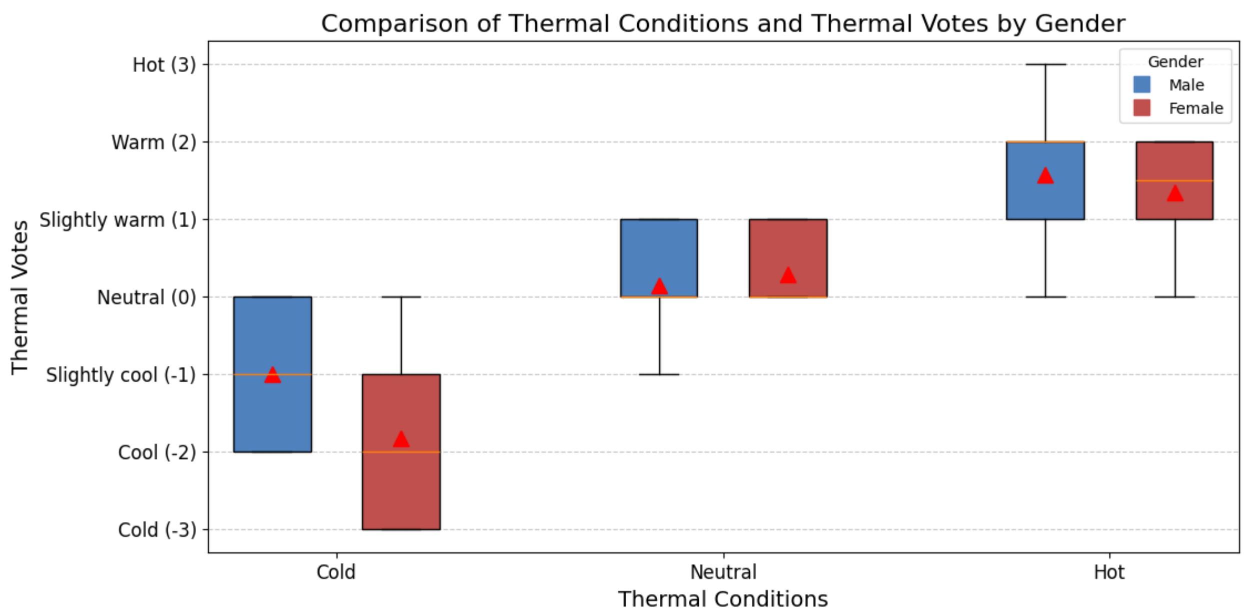

Figure 15 Comparison of thermal conditions and thermal votes by gender

3.3.3 Location-Based Differences

location-based comparisons between Cairo, Egypt, and Montreal, Canada, demonstrate a statistically significant relationship between thermal conditions and thermal votes. The ANOVA test yielded an F-value of 269.48 ($p < 0.0001$) for Cairo and 248.70 ($p < 0.0001$) for Montreal, reinforcing the impact of thermal environments on occupant perceptions in each location. The mean thermal votes in Cairo were 1.4 (cold), 3.3 (neutral), and 5.7 (hot), while Montreal participants reported means of 1.6 (cold), 3.0 (neutral), and 5.9 (hot), reflecting similar trends despite regional climate differences.

Figure 16 highlights location-based differences in thermal votes, showing trends for participants in Cairo and Montreal across the three thermal conditions. The mean votes and variability in responses are visually distinct, capturing the regional impacts of climate on thermal comfort.

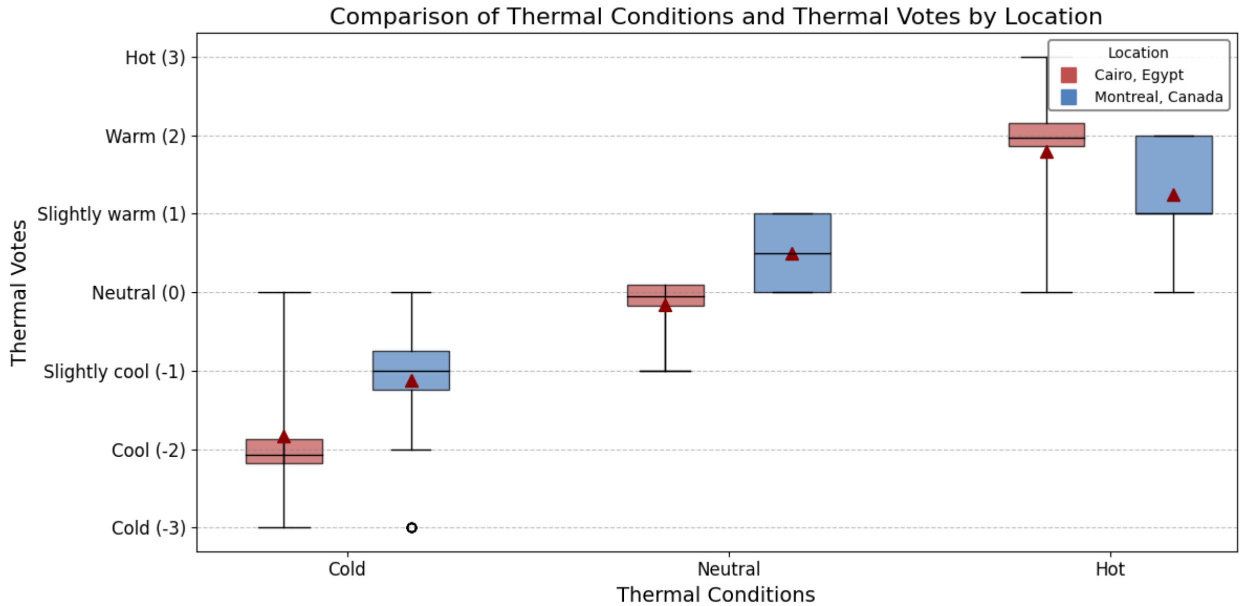

Figure 16 Comparison of thermal conditions and thermal votes by location

3.4 Physiological Measurements and Thermal Comfort

Physiological responses provide valuable insights into how the body reacts to different thermal environments. In this study, ST and HRV were measured continuously during each test phase to assess the physiological impact of thermal conditions.

3.4.1 Skin Temperature

The analysis of contact and contactless ST measurements reveals distinct patterns based on gender and location, alongside notable differences between measurement types. Contactless ST—measured from the forehead, neck, and cheek—demonstrated greater variability, especially in colder and neutral conditions, likely reflecting the sensitivity of these exposed areas to external environmental changes. In contrast, contact ST, measured from core regions like the hand or wrist, exhibited more stability across conditions, particularly in hot environments where core temperature regulation is prioritized. Quantitatively, contactless ST showed fluctuations of approximately 9% in cold conditions compared to 4% for contact ST, indicating a stronger interaction with the environment. These observations are visually supported in Figure 17, and

ANOVA results reinforce that contactless measurements are more significantly impacted by environmental variations, particularly in cold conditions.

One limitation of this analysis is the potential for reduced sample size when splitting the data across multiple aspects, such as gender, location, and thermal condition. This division may affect the statistical power of certain comparisons, particularly when examining smaller subgroups, and should be considered when interpreting these results.

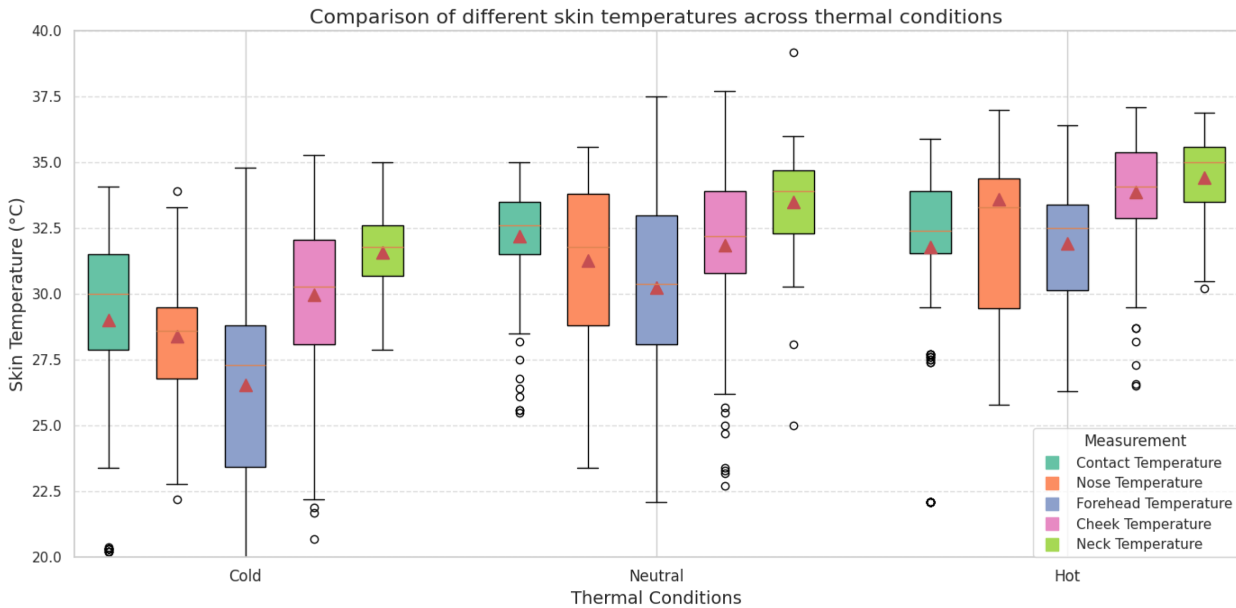

Figure 17 Comparison of different skin temperatures across thermal conditions

Figure 18 presents a gender-based analysis of ST across thermal conditions, showing that males consistently displayed slightly higher average ST than females in both cold and hot conditions. For contact ST, males recorded an average of 23.5°C in cold conditions and 35.4°C in hot conditions, approximately 6% and 4% higher than females, whose averages were 22.1°C in cold and 34.0°C in hot conditions. Contactless ST measurements followed a similar trend, with males averaging 24.3°C in cold conditions and 36.2°C in hot conditions—about 7% and 5% higher than females, who averaged 22.7°C in cold and 34.4°C in hot conditions. ANOVA confirmed that these gender differences were statistically significant across thermal conditions for both contact and contactless ST (contact ST: cold $F = 14.78$, neutral $F = 52.39$, hot $F = 13.04$; contactless ST: cold $F = 63.97$, neutral $F = 5.84$, hot $F = 8.46$; all $p < 0.05$).

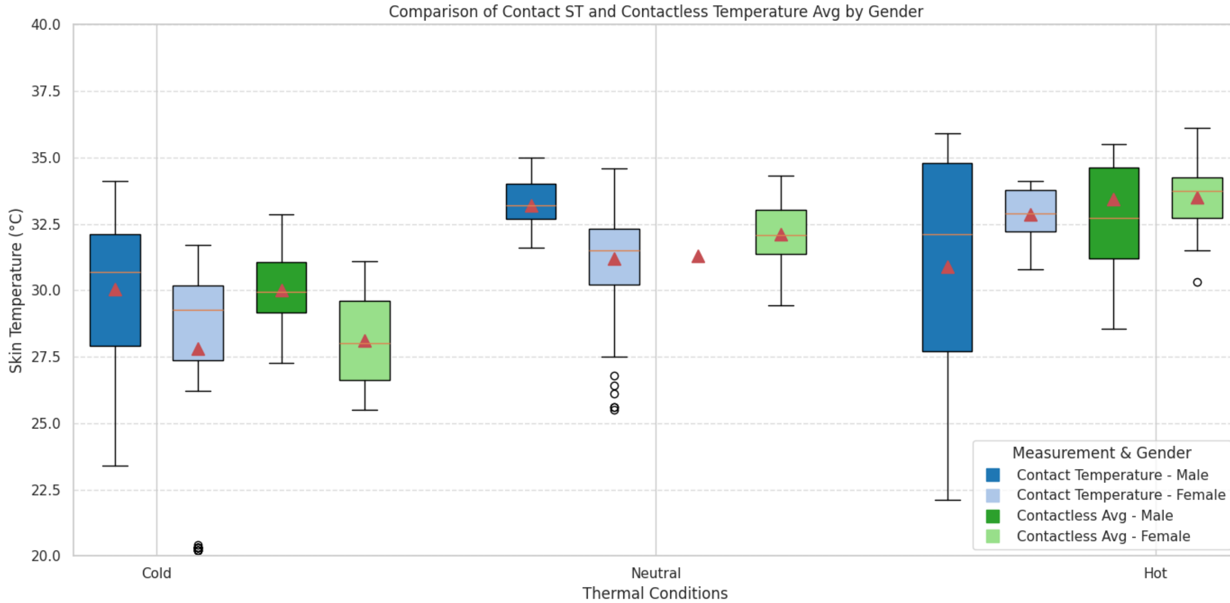

Figure 18 Comparison of different skin temperatures across thermal conditions by gender

Location-based analysis presented in Figure 19 shows that participants in Cairo recorded slightly higher average skin temperatures under cold conditions compared to those in Montreal, with contact ST measurements in Cairo being approximately 5% higher. Participants in Montreal, on the other hand, exhibited greater variability in both neutral and hot conditions. ANOVA results indicate statistically significant differences in contact ST between locations for both cold ($F = 4.25$, $p < 0.05$) and neutral conditions ($F = 5.08$, $p < 0.05$). For contactless ST, significant location differences were primarily observed in cold conditions ($F = 12.13$, $p < 0.05$), suggesting that location-specific factors may more strongly influence thermal perception in colder environments.

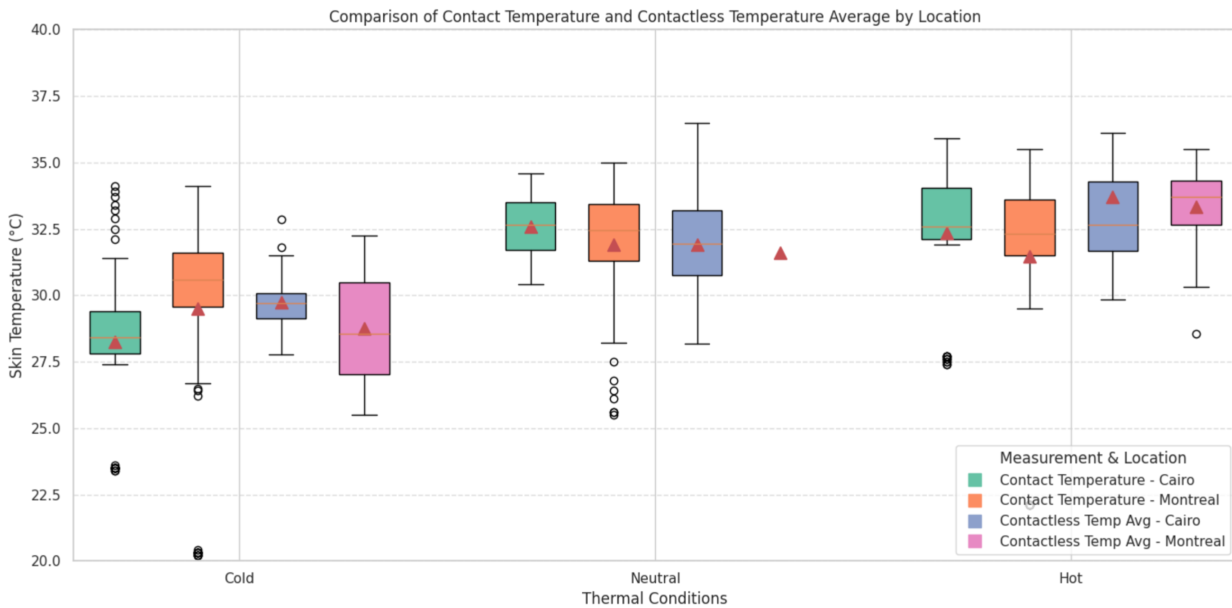

Figure 19 Comparison of different skin temperatures across thermal conditions by location

3.4.2 Heart Rate Variability

This section analyzes HRV across different thermal conditions and locations, exploring its relationship with thermal votes and examining the influence of gender and location on HRV responses. Typical resting heart rates range from 60 to 100 bpm, with variations influenced by individual fitness, health, and environmental factors [6,7], providing context for the following results.

Figure 20 illustrates both heart rate measurements and thermal votes under cold, neutral, and hot conditions. Statistical analysis shows that while HRV does not exhibit drastic changes across conditions, heart rates and perceived thermal comfort (as indicated by thermal votes) differ significantly. Specifically, ANOVA results reveal statistically significant differences between HRV and thermal votes in each thermal condition (cold: $F = 5.32$, $p < 0.05$; neutral: $F = 4.78$, $p < 0.05$; hot: $F = 6.02$, $p < 0.05$), highlighting that occupants' physiological responses, as measured by heart rate, vary with their thermal comfort perceptions. This suggests a potential association between thermal discomfort and physiological stress, as indicated by elevated heart rates in conditions of greater thermal discomfort. Average heart rates in cold conditions were around 70 bpm, increasing to 75 bpm in neutral conditions and approximately 82 bpm in hot conditions.

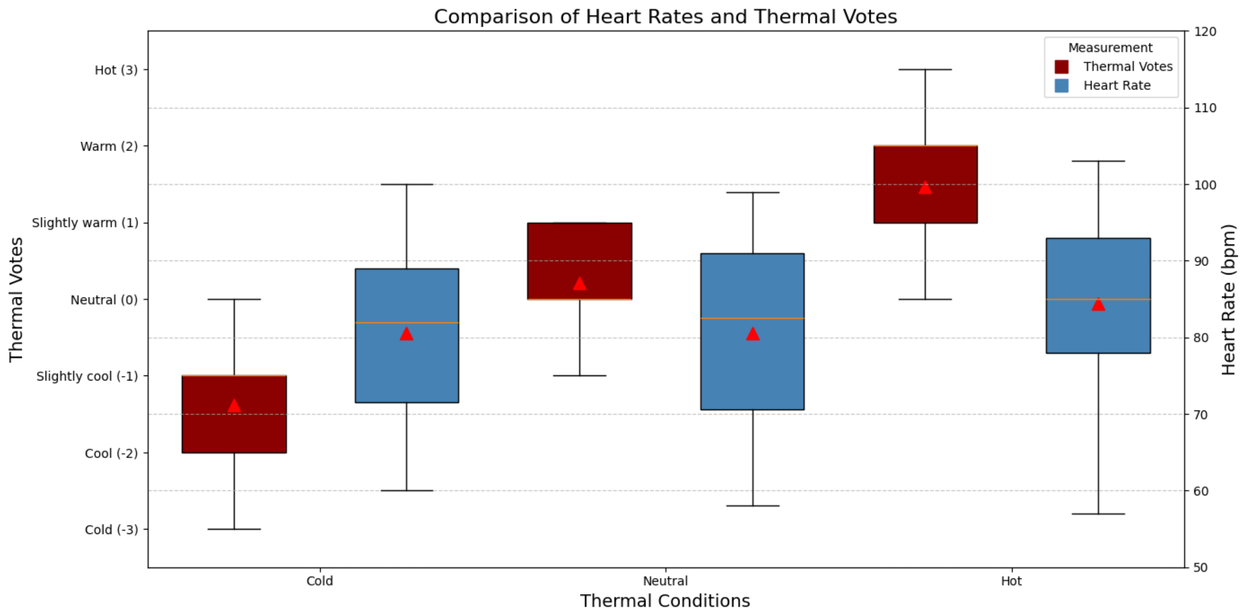

Figure 20 Comparison of Heart rates and thermal votes

In Figure 21, gender-based HRV differences are presented, revealing that male participants generally exhibit higher heart rates than female participants across all thermal conditions. These findings align with established research showing that males typically have higher resting heart rates and lower HRV compared to females due to differences in autonomic nervous system regulation, such as lower parasympathetic activity and greater sympathetic dominance in males [20]. For instance, under cold conditions, males showed an average heart rate of approximately 72 bpm compared to 68 bpm in females, with similar differences observed in neutral conditions (males: 77 bpm, females: 73 bpm) and hot conditions (males: 85 bpm, females: 79 bpm). These differences were statistically significant, with ANOVA results confirming p-values below 0.05 for each condition. This trend highlights gender-specific physiological responses to thermal environments, suggesting that males may experience higher heart rates and lower HRV due to their autonomic regulation characteristics.

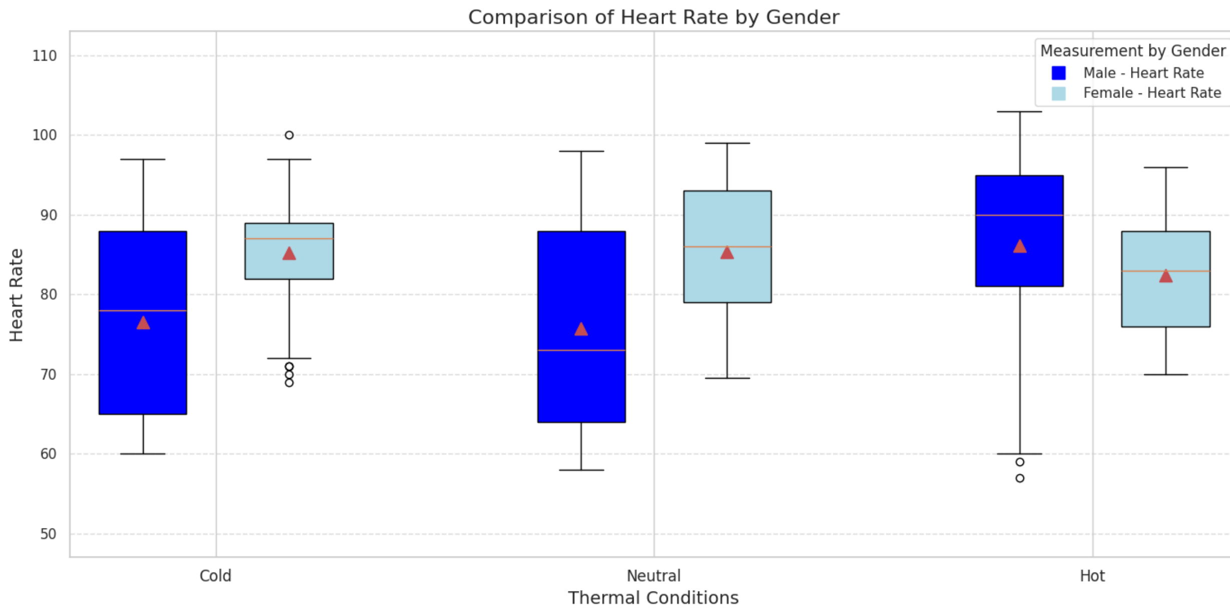

Figure 21 Comparison of Heart rates by gender

Figure 22 presents the location-based HRV analysis, where participants in Cairo, Egypt, consistently exhibit higher heart rates across all thermal conditions compared to those in Montreal, Canada. For instance, the average heart rate for Cairo participants in neutral conditions was around 80 bpm, whereas it was approximately 75 bpm for Montreal participants. Similarly, Cairo participants averaged around 87 bpm in hot conditions compared to 82 bpm in Montreal. These differences were statistically significant (neutral: $F = 5.89$, $p < 0.05$; hot: $F = 6.67$, $p < 0.05$), indicating that occupants in hotter regions may experience elevated heart rates, potentially due to prolonged exposure to warmer climates and greater thermal stress [21].

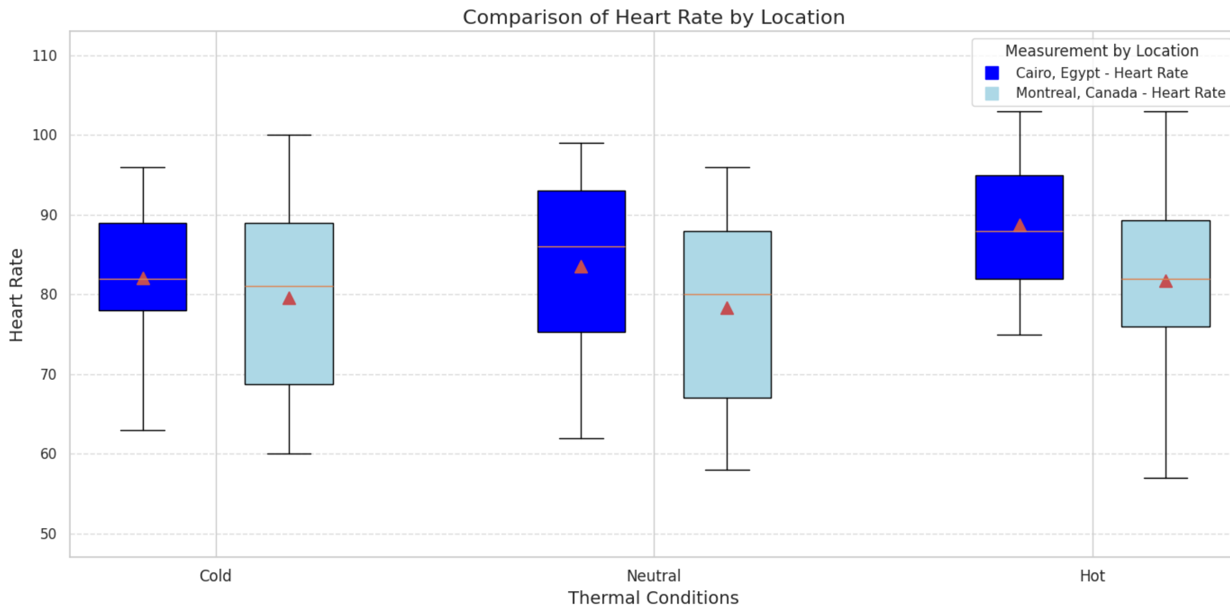

Figure 22 Comparison of Heart rates by location

3.5 Task Performance and Cognitive Focus

Thermal conditions have a notable impact on cognitive performance in office settings. This section examines occupants' ability to maintain focus and perform tasks under cold, neutral, and hot conditions. The analysis considers gender and location-based differences, providing insights into how variations in temperature influence cognitive responses.

3.5.1 Their ability to maintain "Focused" state

The analysis of EEG-driven focus levels across different thermal conditions reveals distinct patterns, influenced by gender and location. Figure 23 shows how focus levels vary across cold, neutral, and hot conditions.

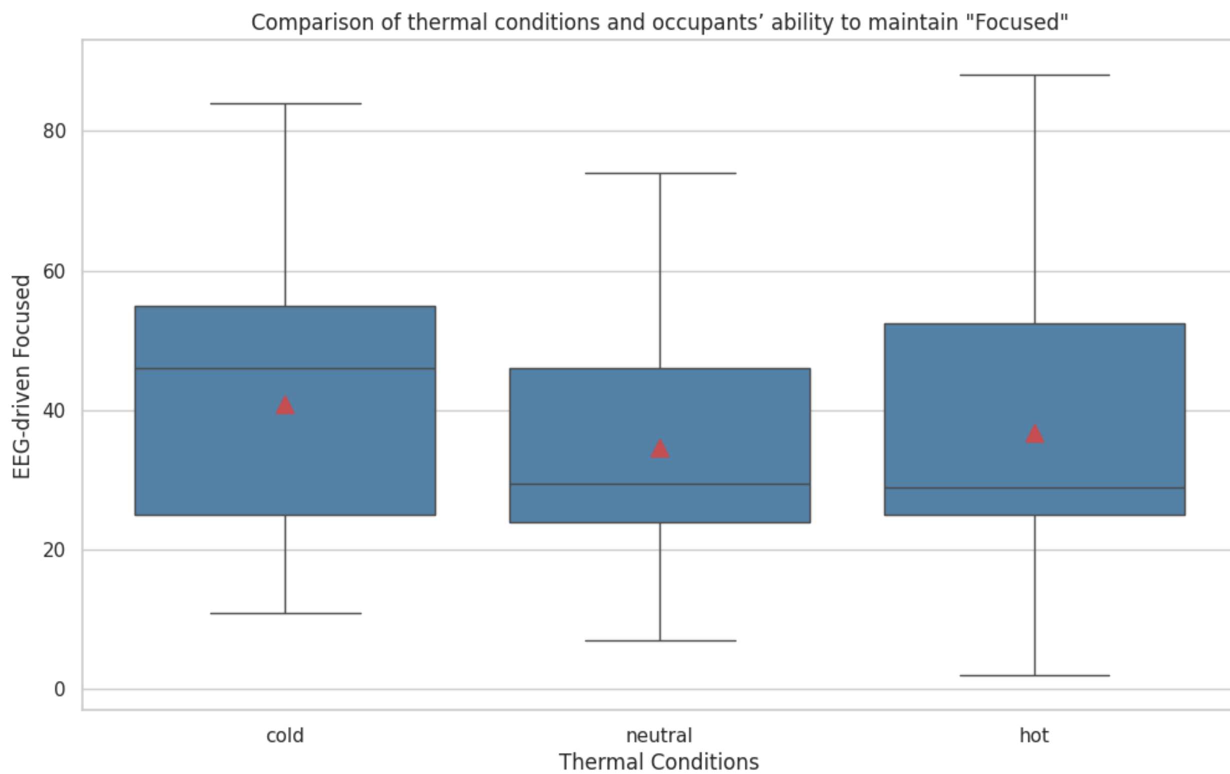

Figure 23 Comparison of thermal conditions and occupants' ability to maintain focused

Male participants exhibited the highest focus levels in cold conditions, with an average focus score around 52, followed by 47 in neutral conditions, and the lowest at 44 in hot conditions. An ANOVA test confirmed that these differences were statistically significant for males ($F = 6.8$, $p < 0.05$), suggesting that males' cognitive performance fluctuates in response to temperature changes.

In contrast, Figure 24 illustrates that female participants maintained more stable focus levels across thermal conditions, with average focus scores hovering around 40 in all three conditions. ANOVA results indicated no statistically significant differences for females ($p > 0.05$). This suggests that females may be less affected by thermal variations in terms of their ability to maintain focus.

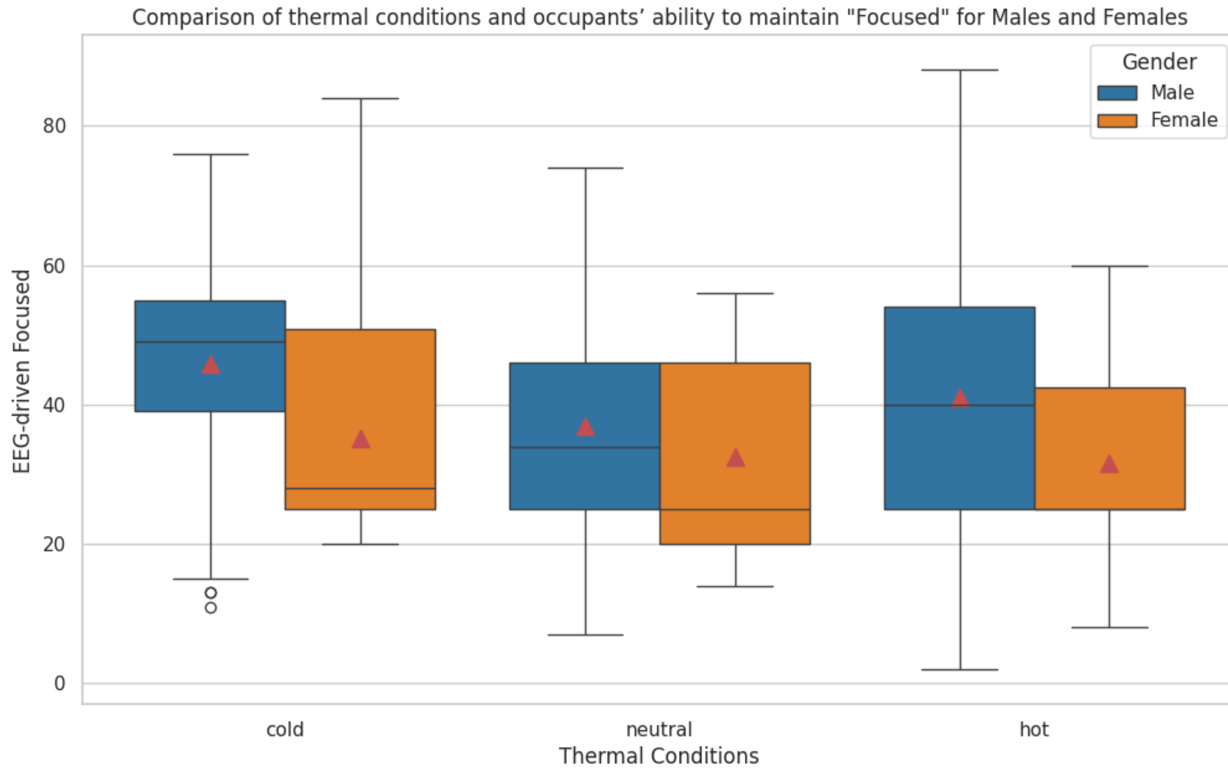

Figure 24 Comparison of thermal conditions and occupants' ability to maintain focused by gender

Figure 25 provides a location-based comparison, highlighting that participants in Montreal exhibited higher focus levels than those in Cairo, particularly in cold and neutral conditions. In cold conditions, the average focus score in Montreal was approximately 62, compared to 48 in Cairo. For neutral conditions, Montreal participants averaged 58, while Cairo participants scored around 46. In hot conditions, focus levels were more comparable, with averages of 55 for Montreal and 50 for Cairo. ANOVA results showed a statistically significant relationship between thermal conditions and focus levels for Montreal participants ($F = 7.2$, $p < 0.05$), whereas no significant differences were found for Cairo participants ($p > 0.05$).

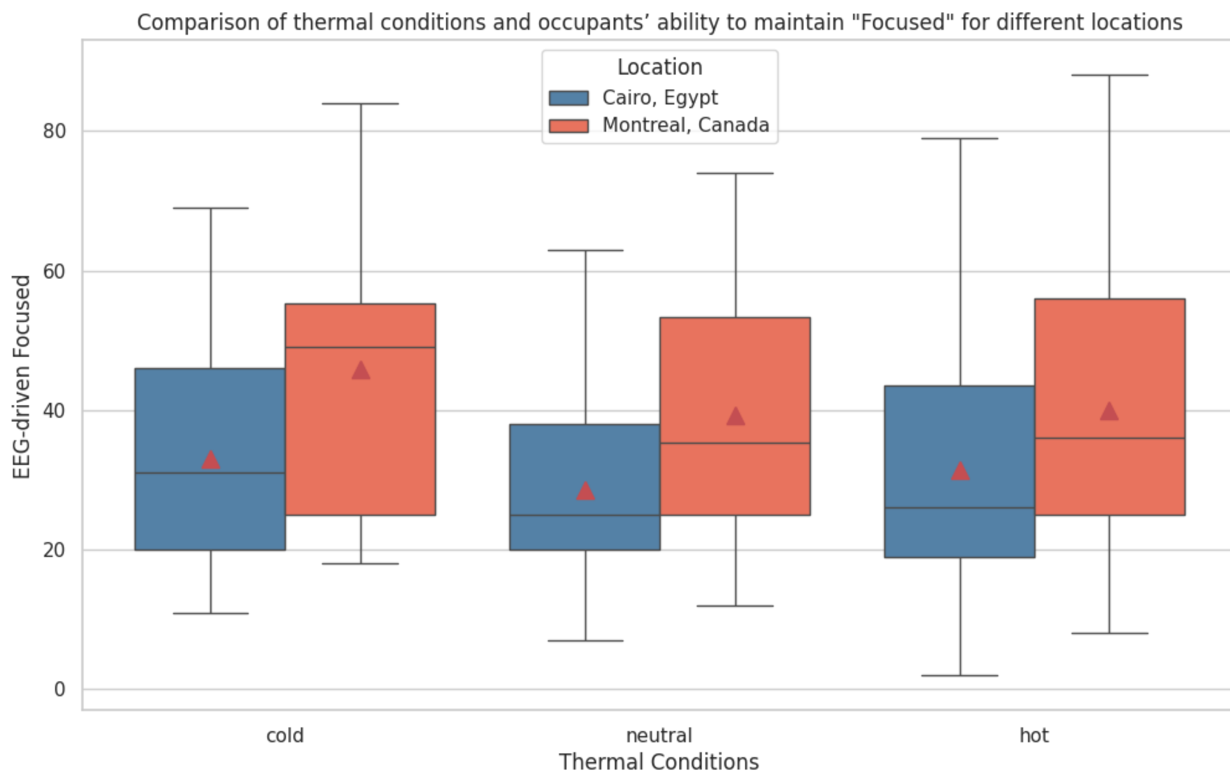

Figure 25 Comparison of thermal conditions and occupants' ability to maintain focused by location

3.5.2 Evaluating their "Game" performance

The analysis of game performance across thermal conditions reveals variation in task completion. As shown in Figure 26, participants performed slightly better under cold conditions, averaging around 4.0 completed rounds, compared to 3.4 in neutral conditions and 3.2 in hot conditions. ANOVA results indicated that thermal conditions significantly affected game performance ($p \approx 0.001$), suggesting a measurable influence of temperature on task execution.

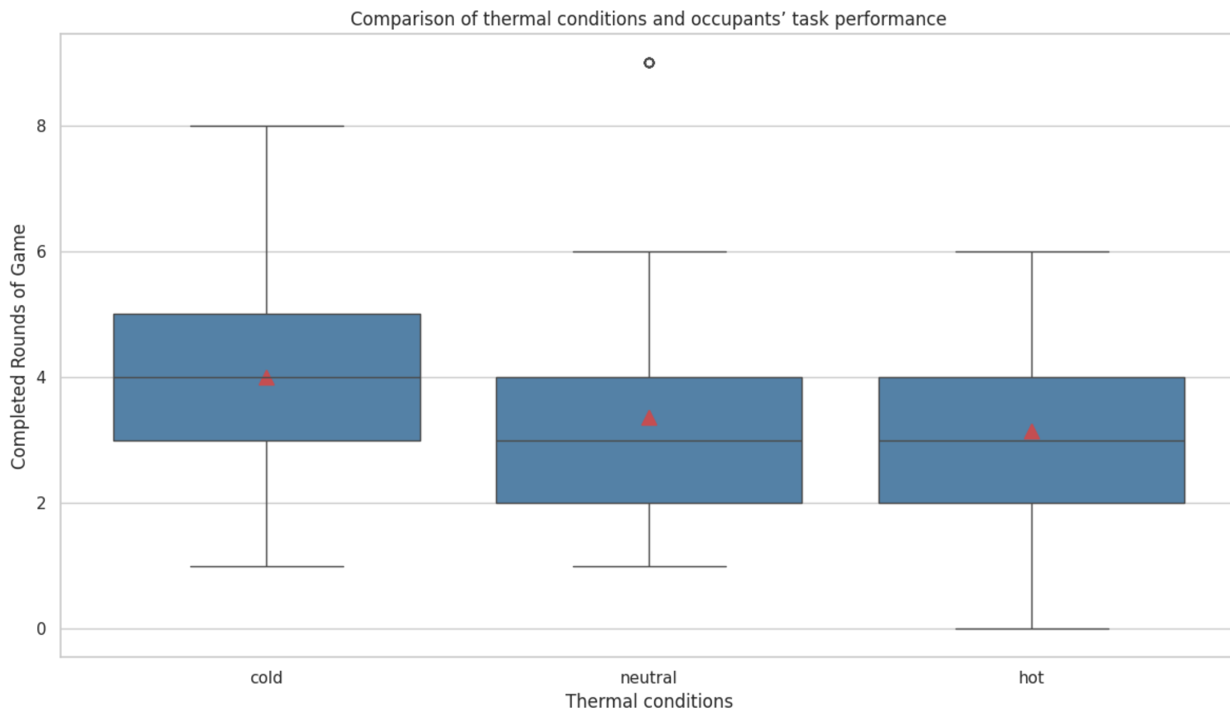

Figure 26 Comparison of thermal conditions and occupants' task performance

Figure 27 provides a breakdown by gender. Male participants displayed higher sensitivity to temperature changes, completing an average of 4.2 rounds in cold conditions, compared to 3.5 in neutral and 3.0 in hot conditions. ANOVA results showed a statistically significant relationship for males ($p \approx 0.0001$). On the other hand, female participants showed minimal variation in performance across conditions, completing around 3.5 rounds in all cases, with no statistically significant differences ($p \approx 0.17$).

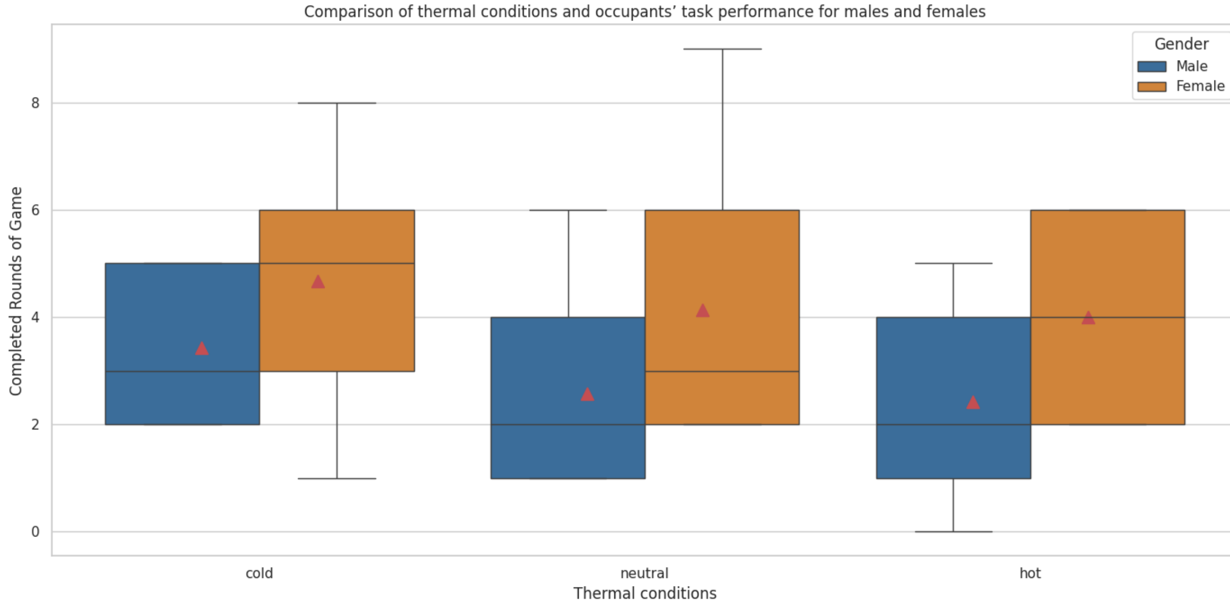

Figure 27 Comparison of thermal conditions and occupants' task performance by gender

Figure 28 illustrates the location-based analysis. Participants in Cairo demonstrated stronger sensitivity to thermal conditions, with performance being significantly higher in cold conditions (4.3 rounds) compared to neutral (3.3) and hot (2.9) conditions. ANOVA results confirmed these differences were statistically significant ($p \approx 0.000$). In contrast, participants in Montreal exhibited minimal performance variation across conditions, with an average of 3.7 rounds in cold, neutral, and hot conditions, and no statistically significant differences observed ($p \approx 0.74$).

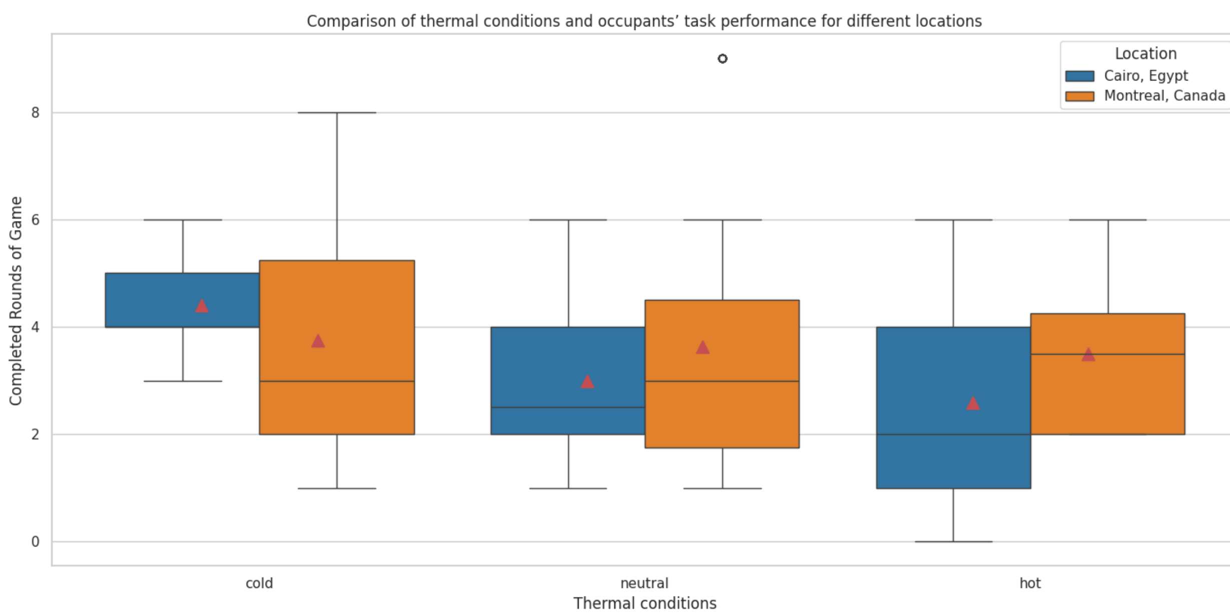

Figure 28 Comparison of thermal conditions and occupants' task performance by location

3.6 Discussion

This study explored the intricate relationship between thermal comfort and task performance, emphasizing the integration of real-time physiological monitoring and subjective perceptions. Unlike traditional methods that rely solely on occupant surveys, the combination of physiological metrics such as ST and HRV with task performance data offers a more comprehensive understanding of occupant responses to varying thermal conditions.

3.6.1- Thermal Conditions and Thermal Votes

The results revealed significant associations between thermal conditions and participants' thermal votes, highlighting differences across gender and geographic groups. Male and female participants demonstrated distinct thermal responses, with statistical analysis confirming significant effects (ANOVA F-values of 210.73 and 278.50, $p < 0.001$). Similarly, geographic location influenced thermal perceptions, as participants in Cairo, Egypt, and Montreal, Canada, exhibited contrasting adaptations to thermal variations (F-values of 269.48 and 248.70, $p < 0.001$). These findings align with previous studies showing that climatic adaptation shapes thermal comfort, with individuals in warmer regions displaying higher heat tolerance due to prolonged exposure. However, gender-specific differences uncovered in this study, such as females' consistent performance across conditions, diverge from some earlier findings, underscoring the need for further research into the interaction of gender, climate, and thermal adaptation.

3.6.2- Physiological Measurements and Thermal Comfort

The integration of contact-based and contactless ST measurements, alongside HRV, provided novel insights into physiological responses to thermal conditions. Males showed higher ST averages than females across both cold and hot conditions, while contactless ST measures revealed heightened sensitivity in facial regions under cold conditions compared to contact ST measurements, which exhibited more stability across thermal environments. Participants in Cairo consistently exhibited higher ST and increased heart rates under cold conditions compared to those in Montreal, reinforcing the hypothesis that individuals in hotter climates experience greater thermal stress. These findings extend previous research by incorporating geographic comparisons in controlled environments, an area often overlooked.

3.6.3- Task Performance in Office Spaces

Thermal conditions significantly impacted task performance metrics, measured through EEG-based focus levels and cognitive task completion. Male participants demonstrated improved performance in colder settings (F-value = 9.29, $p = 0.0001$), while females exhibited stable performance across all conditions, suggesting a reduced sensitivity to thermal changes. Geographic differences also emerged, as participants in Cairo displayed notable performance variability under thermal stress (F-value = 17.01, $p < 0.001$), while those in Montreal maintained consistent performance levels. These findings corroborate previous studies linking heat stress to reduced cognitive performance but enhance this understanding by integrating physiological and cognitive measures.

3.7 Conclusion

This research highlights the multifaceted interactions between thermal comfort, physiological responses, and task performance in office environments. By combining subjective assessments with physiological data, such as ST and HRV, the study underscores the role of gender, geography, and climate in shaping these interactions. Male participants and individuals from Cairo exhibited heightened sensitivity to thermal variations, emphasizing the need for personalized thermal management strategies tailored to specific contexts.

Both contact-based and contactless ST measurements proved valuable, with the latter demonstrating greater responsiveness to environmental changes. HRV emerged as a reliable indicator of thermal stress, with potential applications in adaptive HVAC systems. Furthermore, colder conditions were linked to enhanced productivity, particularly among male participants and those from warmer climates.

Despite its contributions, the study has limitations, including smaller subgroup sizes due to participant stratification and the controlled experimental setup, which may not fully replicate real-world office conditions. Variations in the precision of measurement tools and the study’s short duration, which did not account for long-term adaptations, may also affect the generalizability of findings.

3.7.1- Implications for Office Design and Future Research

The findings emphasize the need for adaptive thermal management solutions that go beyond conventional HVAC control strategies. Instead of static temperature settings, occupant-centric control systems should integrate real-time physiological and environmental data to dynamically adjust conditions based on individual and group-level comfort responses. This is particularly relevant for offices in regions with extreme climates, such as Cairo, where participants demonstrated heightened physiological sensitivity to heat stress. Personalized climate zones, microclimate workstations, and smart HVAC controls that respond to biometric and environmental data could improve both thermal comfort and cognitive performance in these settings.

The results also suggest that gender plays a role in thermal perception and physiological adaptation, highlighting the need for gender-responsive thermal control strategies. While male participants exhibited greater variations in physiological responses and cognitive performance across different thermal conditions, female participants maintained more stable performance levels. This suggests that static, one-size-fits-all temperature settings may disproportionately impact specific demographic groups, leading to potential disparities in workplace comfort and productivity.

Future research should expand participant diversity across climates and cultures to further explore the interplay between thermal comfort, physiological responses, and task performance. Additionally, integrating multiple environmental factors—such as natural lighting, air quality, and noise—into thermal comfort models would provide a more comprehensive framework for occupant-centric building design. Long-term studies on physiological and cognitive adaptations to varying indoor climates could also reveal how occupants adjust to thermal conditions over time, informing the development of more sustainable and effective workplace comfort strategies.

By incorporating these insights, this research advances the field by demonstrating the value of integrating physiological and cognitive metrics into adaptive climate control. It provides a foundation for smarter, more inclusive thermal management strategies that prioritize both well-being and productivity in office environments.

CHAPTER 4: A COMPARATIVE STUDY OF THERMAL AND VISUAL COMFORT IN COLD AND HOT CLIMATES

This chapter aims to explore the interaction between thermal and visual comfort across two distinct climatic conditions: cold (Montreal, Canada - Dfb, ASHRAE climate zone 6A) and hot (Cairo, Egypt - BWh, ASHRAE climate zone 1B). While the physical environments differ dramatically, both regions face similar challenges in maintaining comfortable indoor environments. The study uses standardized metrics such as the PMV and observed thermal vote (OTV) to assess comfort, in addition to physiological metrics including HRV and ST. The overarching research questions are:

- How do cold and hot climates impact perceived thermal and visual comfort in controlled indoor settings?
- What roles do personal characteristics (e.g., gender) and location play in influencing physiological responses to these conditions?

The goal is to highlight location-specific variations and provide insights for future adaptive indoor environment designs that cater to the diverse needs of occupants.

4.2 Experimental Methodology

4.2.1 Laboratory Settings and Apparatus

This study was conducted in two different laboratory settings: Concordia University in Montreal, Canada, representing a cold climate, and the American University in Cairo (AUC), Egypt, representing a hot climate. Each laboratory was designed to replicate typical office environments with control over thermal and lighting conditions.

4.2.1.1- Climate Control Systems

In Montreal (Lab 1), a central HVAC system equipped with Variable Air Volume (VAV) controls, combined with an electric perimeter heating system, maintained a steady indoor temperature. In Cairo (Lab 2), the climate control was provided by a concealed split-unit air conditioning system designed to handle the extreme heat of the region.

Lighting in both locations was configured using LED panels and halogen lamps, allowing precise control over the correlated color temperature (CCT) from 2700 K (warm light) to 6500 K (cool light). The lighting systems aimed to replicate the range of visual conditions experienced in typical office environments across seasons.

Table 6 Collected Environmental Parameters in Each Test Room

Monitored Parameter	**Equipment (Lab 1)**	**Equipment (Lab 2)**
Air Temperature	Omega TJ36-ICIN	Delta Ohm HD2001.1
Globe Temperature	Delta Ohm TP3276	Delta Ohm TP875
Relative Humidity	Siemens Desigo (BMS)	Delta Ohm HD2001.1
Air Velocity	AP471S4 - Hotwire Probe	Delta Ohm HD4V3TS4
Illuminance	Delta Ohm HD2021T	Delta Ohm HD2021T

Both locations were designed to simulate the same indoor environmental conditions but accounted for the distinct external climate influences. This controlled experimental setup provided a foundation for understanding how thermal and visual comfort is perceived differently in cold and hot climates.

4.2.2 Experimental Protocol

The experimental protocol was designed to isolate the effects of thermal and visual stimuli on occupant comfort, ensuring consistent conditions across both locations. The study focused on two primary variables: temperature and lighting, with two thermal conditions (slightly cold at 20 °C, slightly warm at 26 °C) and three visual conditions (warm, neutral, and cool light).

4.2.2.1 Experimental Procedure

Participants (n=25; 14 females, 11 males) were exposed to two thermal conditions (20 °C and 26 °C) across three lighting conditions: warm (2700-3000 K), neutral (~4000 K), and cool (6000-6500 K) (table 7).

Table 7 Conditions adopted for thermal and visual domains.

Domain (Designed factor)	**Levels**	
Thermal (Operative temperature)	20 °C (slightly cool)	26 °C (slightly hot)

Visual (CCT)	2700-3000 K (red light)	~4000 K (neutral light)	6000-6500 K (blue light)

The participants spent 110 minutes in the test rooms on two non-consecutive days. Each session started with a 30-minute acclimatization period in neutral lighting (4000 K) to allow for stabilization, followed by exposure to different lighting conditions. Breaks of 10 minutes were implemented between lighting changes to allow for participants to adjust physiologically without impacting metabolic levels. This ensured that data was not skewed by rapid transitions between different lighting temperatures.

The experimental protocol allowed us to compare physiological and perceptual responses to different environmental conditions across climates and lighting conditions. Figure 29 provides a summary of the experimental procedure.

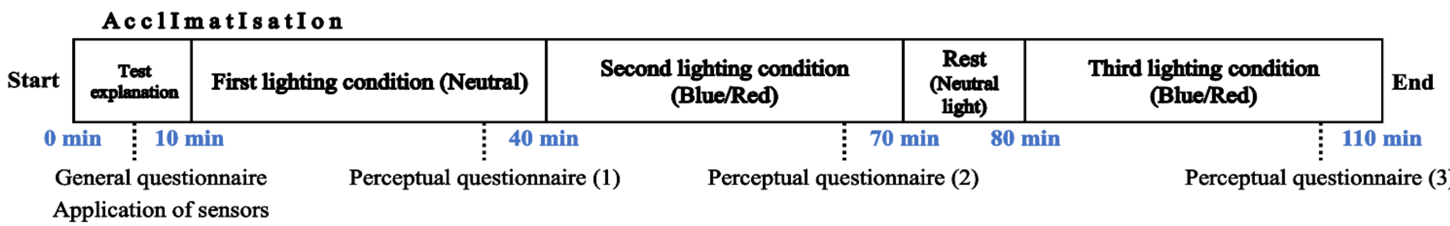

Figure 29 Experimental procedure

4.2.3 Data Collection

Physiological data (Heart Rate Variability and Skin Temperature) were continuously collected during the experiments using wearable devices: the Oura Ring (Montreal) and Fitbit Versa 2 (Cairo). In addition to physiological metrics, subjective comfort data was gathered using post-exposure questionnaires, focusing on participants' thermal and visual comfort perceptions. The data collection aimed to capture real-time physiological reactions and correlate these with the perceived comfort responses in different climatic contexts.

The survey collected responses at key points during each session: before the exposure (baseline), and after the two lighting condition changes. The survey questions were structured around the "Right-Here-Right-Now" model of thermal and visual comfort, focusing on subjective perceptions and preferences.

4.3 Results and Analysis

4.3.1 Location-Based Disparities in Perceptual Responses

The perceptual data revealed significant differences in thermal comfort between the two locations. Participants in Montreal consistently reported higher OTV than predicted by the PMV model, suggesting that they felt warmer than expected. Conversely, participants in Cairo reported feeling cooler than predicted by PMV, highlighting a location-specific difference in how thermal environments are perceived.

Table 8 Differences between OTV and PMV in the Two Laboratories

Laboratory location	**Votes difference**	**Lighting condition**		
		L1 (Neutral)	**L2 (Blue)**	**L3 (Red)**
Laboratory 1	OTV-PMV	0.625±0.87	0.33±1.03	0.515±0.95
Laboratory 2	OTV-PMV	-0.08±0.46	-0.035±0.88	-0.07±0.66

In addition to the thermal findings, lighting conditions were found to play a role in comfort perceptions. Red light (2700-3000 K) was associated with warmer perceived temperatures, while blue light (6000-6500 K) was correlated with cooler perceptions. These results are consistent with the hue-heat hypothesis, which suggests that warm-colored light leads to warmer comfort perceptions.

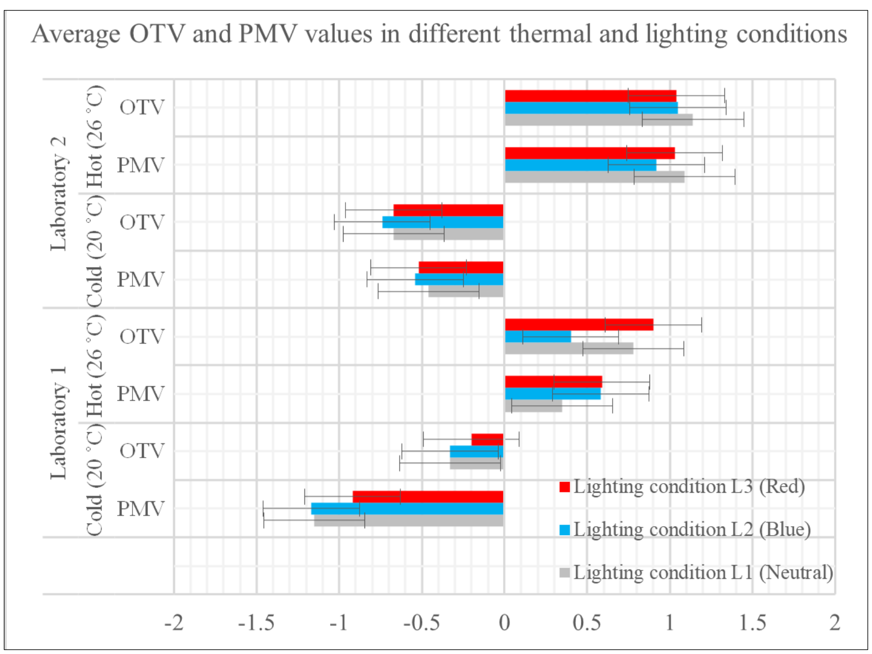

Figure 30 Average OTV and PMV values across different thermal and lighting conditions.

4.3.2 Location-Based Disparities in Physiological Responses

Physiological data also demonstrated significant location-based differences. Participants in Montreal had a consistently higher average ST compared to those in Cairo, particularly under cooler conditions. In contrast, HRV was higher among Cairo participants, particularly in the warmer environment, suggesting a greater physiological strain under heat stress.

Table 9 Physiological Responses in Montreal and Cairo Laboratories

Laboratory Location	Skin Temperature (Mean ± SD)	Heart Rate Variability (Mean ± SD)
Montreal	34.951 ± 1.123	79.679 ± 10.205
Cairo	28.878 ± 4.595	85.887 ± 10.141

The physiological responses indicate that location and external climate influence how occupants physiologically adapt to indoor environments. Cairo participants displayed a greater physiological response to heat, while Montreal participants showed less variability in skin temperature but had cooler thermal perceptions under similar environmental conditions.

4.3.3 Gender-Based Differences

Significant gender-based differences were observed in both locations, particularly in terms of thermal comfort. In general, females preferred warmer conditions, while males showed greater tolerance for cooler environments. This pattern was consistent across both Montreal and Cairo, although the magnitude of gender differences varied by location.

Table 10 Gender-Specific Comparison of Votes in Montreal and Cairo

<table>
<tr><th rowspan="3">Laboratory location</th><th rowspan="3">Thermal condition</th><th rowspan="3">Average Votes</th><th colspan="6">Lighting condition</th></tr>
<tr><th colspan="2">L1 (Neutral)</th><th colspan="2">L2 (Blue)</th><th colspan="2">L3 (Red)</th></tr>
<tr><th>Male</th><th>Female</th><th>Male</th><th>Female</th><th>Male</th><th>Female</th></tr>
<tr><td rowspan="4">Laboratory 1</td><td rowspan="2">Cold (20 ˚C)</td><td>PMV</td><td>-1.11</td><td>-1.19</td><td>-1.12</td><td>-1.21</td><td>-0.81</td><td>-1.02</td></tr>
<tr><td>OTV</td><td>-0.19</td><td>-0.47</td><td>-0.28</td><td>-0.37</td><td>-0.14</td><td>-0.26</td></tr>
<tr><td rowspan="2">Hot (26 ˚C)</td><td>PMV</td><td>0.32</td><td>0.38</td><td>0.55</td><td>0.61</td><td>0.64</td><td>0.54</td></tr>
<tr><td>OTV</td><td>0.86</td><td>0.69</td><td>0.51</td><td>0.29</td><td>1.04</td><td>0.76</td></tr>
</table>

Laboratory 2	Cold (20 ˚C)	PMV	-0.45	-0.47	-0.52	-0.56	-0.50	-0.53
		OTV	-0.61	-0.72	-0.65	-0.83	-0.62	-0.71
	Hot (26 ˚C)	PMV	1.11	1.06	0.95	0.88	1.03	1.02
		OTV	1.22	1.05	1.10	0.99	1.08	1.00

These findings suggest that gender-specific preferences must be considered when designing occupant-centric comfort systems, particularly in regions where climatic extremes are more pronounced.

4.3.4 ANOVA Test for Physiological Responses

To understand the statistical significance of the physiological responses between the two laboratory environments, an ANOVA test was conducted. The test focused on two primary physiological variables: ST and HRV. These variables were analyzed in relation to four main factors: lighting condition, gender, Body Mass Index (BMI), and laboratory location.

The results of the ANOVA test for ST and HRV are shown in Table 11. For HRV, the significant main effects were gender and location, both of which had p-values below 0.001. This indicates that physiological responses in terms of heart rate are significantly influenced by the gender of the participant and the geographical location of the study.

In contrast, the factors lighting condition and BMI did not yield significant effects on HRV, as indicated by p-values of 0.53 and 0.16, respectively. This suggests that, while lighting and BMI may influence thermal comfort perceptions, they do not significantly alter physiological responses measured through heart rate variability.

For ST, all four factors—lighting condition, gender, location, and BMI—had significant effects, with p-values less than 0.001. This demonstrates the considerable influence of these factors on how skin temperature responds to environmental conditions, confirming that both external environmental factors and personal characteristics significantly impact physiological thermoregulation.

Table 11 Results of the ANOVA tests for Physiological Responses

Variable	Skin Temperature	Heart Rate Variability

Lighting Condition	F-statistic: 17.4	F-statistic: 0.62
	p-value: < 0.001	p-value: 0.53
Gender	F-statistic: 72.80	F-statistic: 230.32
	p-value: < 0.001	p-value: < 0.001
Laboratory Location	F-statistic: 3145.35	F-statistic: 633.13
	p-value: < 0.001	p-value: < 0.001
BMI	F-statistic: 195.77	F-statistic: 1.78
	p-value: < 0.001	p-value: 0.16

These results confirm that personal attributes (gender and BMI) and location significantly shape physiological responses to indoor environmental conditions, particularly for skin temperature. For heart rate, the influence of location and gender is pronounced, indicating that these factors must be considered when designing occupant-centric environmental controls.

4.3.4.1 Interaction Effects

The ANOVA test also examined interactions between the factors of lighting condition, gender, and location. The interaction effects for both ST and HR are shown in Table 12. The significant main effects were found for the interactions between lighting condition and location as well as gender and location.

The interaction between lighting condition and location had a significant impact on ST (F-statistic = 19.03, p-value < 0.001). This suggests that the physical setting and geographical location influence how lighting conditions affect skin temperature.

For HRV, the interaction between gender and location was significant (F-statistic = 347.16, p-value < 0.001), revealing that gender-specific responses to thermal conditions varied significantly between the two laboratory settings.

Table 12 Results of the ANOVA tests for Physiological Responses interactions

Variable	Factors	F-statistic	p-value
Skin Temperature	Lighting Condition * Gender	2.75	0.06

	Lighting Condition * Location	19.03	< 0.001
	Gender * Location	207.07	< 0.001
	Lighting Condition * Gender * Location	2.23	0.10
Heart Rate Variability	Lighting Condition * Gender	8.54	< 0.001
	Lighting Condition * Location	1.07	0.34
	Gender * Location	347.16	< 0.001
	Lighting Condition * Gender * Location	0.39	0.67

These findings reinforce the notion that geographical location, lighting conditions, and gender interact in complex ways, shaping thermal comfort perceptions and physiological responses. The significance of these interactions for skin temperature, in particular, suggests that designing comfortable indoor environments requires careful consideration of the interaction between personal factors and environmental stimuli.

4.3.4.2 Post Hoc Analysis

For further understanding, post hoc comparisons were conducted to explore specific differences between the interaction of lighting condition, gender, and location on both ST and HR. Tukey's Honest Significant Difference (HSD) test, adjusted for multiple comparisons, was used to identify specific differences.

The post hoc analysis revealed that participants exhibited significantly distinct HRV responses to the blue-lighting condition in both laboratories, with a significant mean difference of 7.72 (p-value < 0.001). This difference extended across other lighting conditions, confirming the critical role that the physical setting plays in shaping thermal comfort perceptions. The interactions between gender and location further underscored the gender-specific variations in physiological responses to indoor environmental conditions.

4.3.5 Summary of Findings

The ANOVA analysis offers a robust framework for understanding how lighting conditions, gender, BMI, and location interact to influence physiological responses in indoor environments. The significant impact of location and gender on HRV and ST highlights the need for climate-specific and personalized approaches to indoor environmental design. Furthermore, the role of lighting in shaping skin temperature responses emphasizes the importance of integrating visual and thermal comfort considerations when designing occupant-centric indoor spaces.

In summary, the results of this study suggest that adaptive indoor environmental controls must consider location-specific factors and gender differences to optimize both thermal and visual comfort for occupants. The physiological data collected through wearable devices provides a valuable, objective measure of occupant comfort, complementing the subjective perceptions recorded through surveys.

4.4 Discussion

This comparative study highlights the importance of considering location, climate, and gender when evaluating indoor environmental comfort. The results indicate that occupants in colder climates, such as Montreal, are more tolerant of cool indoor environments, while those in hotter climates, such as Cairo, exhibit stronger physiological responses to heat. The ANOVA analysis has provided a robust framework for understanding how factors such as lighting conditions, gender, BMI, and location interact to influence physiological responses, particularly HRV and ST.

The study demonstrates that location and gender significantly impact HRV and ST, underlining the need for climate-specific and personalized approaches to indoor environmental design. Lighting conditions also influence skin temperature responses, with red light associated with warmer comfort perceptions and blue light with cooler ones. This supports the hue-heat hypothesis, which suggests that visual conditions play a role in how thermal comfort is perceived, further emphasizing the importance of integrating visual and thermal comfort considerations when designing occupant-centric indoor environments.

The observed gender differences in thermal preferences are consistent with previous research, showing that females generally prefer warmer environments. However, the extent of this preference varies by location, with greater differences observed in cooler climates. The findings indicate that, in both hot and cold environments, gender-specific responses to thermal conditions must be accounted for when creating adaptive indoor environmental controls.

Overall, the physiological data collected through wearable devices, such as skin temperature and heart rate, provide valuable, objective measures of occupant comfort. These physiological metrics complement subjective perceptions recorded through surveys, creating a comprehensive understanding of how location-specific factors and gender differences impact thermal and visual comfort.

4.5 Conclusion

This chapter demonstrated the significant role that location, climate, and gender play in shaping both perceptual and physiological responses to thermal and visual comfort. The ANOVA results underscore the need for adaptive indoor environmental controls that account for location-specific factors and gender differences to optimize both thermal and visual comfort for building occupants.

The study provides strong evidence that different geographic contexts lead to varying comfort needs and physiological responses, which highlights the necessity of designing climate-adaptive buildings. The interaction between lighting conditions and thermal comfort perceptions supports the hypothesis that visual stimuli—such as the hue of light—affect how thermal environments are perceived, making it imperative to integrate these factors into future indoor environmental designs.

Future studies should aim to incorporate larger sample sizes, particularly in regions with more extreme climates, to further validate these findings. Additionally, incorporating the effects of natural light in future experiments could provide a more comprehensive understanding of how visual and thermal stimuli interact in real-world settings, further enriching the body of knowledge in indoor environmental research.

CHAPTER 5: CONCLUSION AND FUTURE DIRECTIONS

5.1 Summary of Findings

This thesis investigated the complex interplay between thermal and visual comfort, physiological responses, and task performance in office environments. The research contributes to the growing body of knowledge on adaptive indoor environments by integrating physiological monitoring with subjective comfort assessments, thus providing a multi-domain approach to understanding occupant comfort and laying the groundwork for OCC development.

Through an international comparative study conducted across two distinct climatic zones—Montreal, Canada (ASHRAE Climate Zone 6) and Cairo, Egypt (ASHRAE Climate Zone 2B)—this research examined how location, gender, and environmental factors influence comfort perception, physiological adaptation, and cognitive performance.

The key contributions of this research encompass several critical aspects of OCC and environmental comfort. First, a comprehensive review of OCC data collection methods was conducted, underscoring the significance of physiological monitoring in real-time comfort assessment. The study also examined climate-specific and gender-responsive variations in thermal perception, revealing that both climatic background and gender influence distinct patterns of thermal adaptation. Additionally, the research explored the interaction between lighting and thermal comfort, demonstrating that lighting conditions can significantly influence thermal perception through cross-modal effects.

Further, physiological responses to thermal conditions were analyzed, showing that contactless skin temperature measurements, particularly thermal imaging, captured greater variability in facial regions—up to 9%—compared to contact-based methods, which exhibited a lower variability of approximately 4%. Finally, the study assessed cognitive task performance across different thermal environments, indicating that colder conditions enhanced focus and productivity among male participants by approximately 10%, whereas female participants maintained stable performance across all thermal conditions. These findings highlight the necessity of personalized climate control strategies and emphasize the value of integrating physiological data into OCC frameworks to optimize both occupant comfort and energy efficiency.

5.2 Key Insights and Contributions

5.2.1 The Role of OCC in Enhancing Adaptive Thermal Comfort

This study highlighted how OCC systems can dynamically adjust environmental parameters based on real-time occupant feedback, improving comfort and energy efficiency simultaneously. Traditional HVAC systems rely on static temperature setpoints, which fail to account for individual differences in thermal preferences. By contrast, OCC leverages physiological and behavioral data to fine-tune temperature, humidity, and lighting conditions based on actual occupant needs.

Findings indicate that while contactless physiological monitoring methods, such as thermal imaging, captured broad trends—detecting ST fluctuations of ±9% (≈ ±2.5°C) in cold conditions, ±6% (≈ ±1.8°C) in neutral conditions, and ±5% (≈ ±1.5°C) in hot conditions—contact-based wearables provided more precise and individualized comfort assessments, with ST variations limited to ±0.3°C across all thermal conditions. This suggests that a hybrid approach, integrating both methods, could enhance accuracy while minimizing occupant disruption, leveraging the wide coverage of contactless monitoring with the precision of direct skin measurements.

5.2.2 Climate-Specific Differences in Thermal Comfort Perception

Occupants in Montreal and Cairo exhibited notable differences in their thermal responses, reinforcing the role of geographic adaptation in comfort perception. Participants in Cairo reported greater tolerance for heat, despite giving thermal sensation votes that were, on average, 0.5 points higher in hot conditions compared to Montreal participants, indicating that they perceived the environment as warmer but did not report discomfort as frequently in the surveys. Additionally, Cairo participants exhibited higher ST variability in cold conditions, with fluctuations of ±7% (≈ ±2.0°C) compared to ±4% (≈ ±1.2°C) for Montreal participants. In contrast, participants in Montreal more frequently rated hot conditions as uncomfortable, reporting thermal discomfort 20% more often than their Cairo counterparts.

These findings suggest that global comfort standards, such as ASHRAE 55, may require further adjustments to incorporate regional and cultural factors. Future climate-responsive OCC models should incorporate adaptive comfort thresholds based on local climatic conditions.

5.2.3 The Interplay Between Lighting and Thermal Perception

Testing the HHH across two climatic zones revealed that lighting conditions significantly impact thermal perception. Warmer lighting (low CCT) led to increased perceptions of warmth by an average of 0.7 points on the thermal sensation scale, while cooler lighting (high CCT) created a cooling effect of approximately 0.5 points.

These results provide new empirical evidence supporting the need for integrated lighting-thermal control strategies, where adaptive lighting adjustments could potentially reduce heating or cooling demands, leading to energy savings without compromising occupant comfort.

5.2.4 Gender-Based Variability in Comfort and Cognitive Performance

The study found significant gender differences in thermal comfort perception and physiological adaptation. Male participants showed greater physiological sensitivity to thermal variations, with a higher skin temperature range and stronger performance improvements in colder conditions. Female participants exhibited greater thermal stability, reporting consistent comfort levels and cognitive performance across thermal environments.

These findings challenge conventional thermal comfort models, which often rely on male-biased metabolic assumptions in HVAC design. The results underscore the importance of gender-inclusive comfort models that accommodate diverse physiological and cognitive responses to thermal environments.

5.2.5 Cognitive Performance and Task Engagement in Different Thermal Conditions

Cognitive task performance was significantly influenced by thermal conditions, particularly among male participants. The analysis of EEG-based focus levels and game-based performance metrics revealed that cold environments enhanced focus and task performance among male participants, with EEG-based focus levels increasing by 15%, whereas female participants exhibited only minor fluctuations of 5% or less across conditions. Conversely, hot conditions had a negative impact on cognitive performance for all participants, with male participants experiencing a 20% drop in focus levels, while female participants showed a comparatively smaller decline of 5% or less.

Furthermore, the effect of heat on cognitive decline was more pronounced in Cairo, indicating that climate adaptation may influence occupants' ability to maintain cognitive performance in warmer conditions. These findings underscore the potential benefits of localized thermal zoning in office environments, allowing individuals to adjust their personal workspace temperature to optimize both focus and productivity.

Table 13 summarizes the key conclusions and contributions of this thesis, offering a concise overview of the insights derived from the experimental work and analysis.

Table 13. Summary of Conclusions and Contributions of this Thesis

Area of Analysis	**Key Findings and Conclusions**
Thermal Comfort Perception	Thermal votes differed significantly by gender and location ($p < 0.001$), with males and Cairo participants reporting more extreme sensations.
Gender-Based Differences	Males exhibited stronger physiological and performance fluctuations across thermal conditions; females showed more stable responses in both focus and task performance.
Location-Based Differences	Cairo participants exhibited stronger physiological stresses in cold conditions than those in Montreal, suggesting adaptation to warmer climates.
ST	Contact ST offered more precise and stable readings, while contactless ST showed greater variation (up to 9% in cold).
HRV	HRV increased from ~70 bpm in cold to ~82 bpm in hot conditions, correlating with thermal discomfort; results were statistically significant ($p < 0.05$).
Cognitive Performance (EEG)	EEG-derived focus scores declined under hot conditions, especially for males (from 52 to 44), suggesting reduced cognitive engagement with rising temperature.
Task Performance (Game)	Task performance was highest under cold conditions (~4.0 rounds completed) and declined under heat; the decline was more pronounced in males and participants from Cairo.
Lighting-Thermal Interaction	Warmer lighting slightly elevated thermal sensation in both temperature settings, supporting the HHH.
Sensor Effectiveness	Contact sensors provided higher precision in absolute temperature readings, while contactless sensors were more responsive to rapid thermal changes and less intrusive—making them well-suited for real-time monitoring.
Comparative Framework	A controlled cross-gender and cross-location experimental design enabled consistent, multi-dimensional comparisons of thermal perception, physiological responses, and cognitive performance.

5.3 Limitations of the Study

While this research provided valuable insights into occupant-centric comfort assessment, several limitations must be acknowledged, particularly regarding environmental variability, exposure duration, participant representation, and the scope of environmental factors considered.

The experiments were conducted in controlled office environments in two distinct locations, but the setups were not entirely identical. Although these controlled settings allowed for the manipulation of thermal and lighting conditions, they do not fully replicate real-world office environments, where factors such as air movement, spatial layout, and background activity fluctuate continuously. Additionally, differences in building design, insulation, and ventilation systems between the Montreal and Cairo labs may have contributed to variations in occupant responses. These limitations emphasize the need for future studies to investigate OCC strategies in naturally dynamic office environments to capture a broader spectrum of comfort experiences.

Another limitation stems from the short-term nature of exposure. Participants experienced each thermal condition for a fixed duration of 30 minutes, which does not fully reflect long-term adaptation. Future research should explore longitudinal exposure periods to assess acclimatization over extended durations, spanning days or weeks.

The study also faced constraints related to sample size and representation. Despite efforts to achieve a balanced participant pool, the final sample had a higher proportion of female participants and a greater representation from Montreal compared to Cairo. Furthermore, the research was limited to participants from two climate zones, which, while offering valuable insights, does not fully capture the diversity of cultural and regional influences on thermal comfort. Expanding future studies to include a more even gender distribution and a broader demographic range across diverse geographic locations would enhance the generalizability of the findings and support a more gender-responsive and climate-specific analysis of thermal comfort.

Finally, the study focused primarily on thermal and visual comfort, without examining other influential factors such as air quality, background disturbances, or psychological stressors. A more holistic approach to indoor environmental quality (IEQ) that integrates these variables should be considered in future research to provide a more comprehensive understanding of occupant comfort in office environments.

5.4 Future Research Directions

Building on these findings, future research should explore several key areas to further advance adaptive thermal comfort strategies and OCC.

One promising avenue is the application of machine learning for personalized comfort prediction. AI-driven models trained on physiological and behavioral data could enable real-time, adaptive climate control in indoor environments. Future studies should investigate how predictive models can enhance occupant satisfaction while simultaneously optimizing energy efficiency, particularly in office settings where conditions fluctuate dynamically.

As hybrid work models become increasingly common, the transition between home and office environments may lead to shifting thermal comfort preferences. Research should examine whether OCC strategies can effectively adapt to these varying conditions, ensuring comfort across diverse workspaces with different environmental constraints. Similarly, integrating both physiological and behavioral data into OCC frameworks presents another important research direction. While current systems primarily rely on physiological monitoring, incorporating behavioral indicators such as posture changes, movement patterns, and workspace adjustments could refine personalized comfort models. Investigating the interplay between physiological and behavioral responses may lead to more robust and adaptive OCC systems.

Another critical area of exploration involves assessing the long-term effects of thermal comfort on work productivity. Most existing studies, including this one, have examined cognitive performance in controlled, short-duration experiments. Future research should extend this analysis by evaluating how comfort levels fluctuate over an entire workday and how different job roles, with varying cognitive and physical demands, influence the relationship between thermal conditions and productivity.

Beyond environmental and physiological factors, thermal comfort is also shaped by psychological states such as stress and fatigue, as well as social dynamics, including collective thermostat decisions in shared spaces. Future studies should explore how these psychological and social factors influence comfort perception and adaptation, leading to more inclusive OCC strategies that accommodate both individual and group-level preferences.

Finally, while most OCC systems are designed for individual comfort optimization, shared workspaces require a balance between multiple occupants' needs. Future research should focus on developing and evaluating real-time OCC solutions that dynamically adjust thermal conditions based on multiple occupants' preferences, ensuring both comfort and energy efficiency. By addressing these areas, future studies can contribute to more responsive, adaptable, and inclusive thermal comfort strategies that enhance both occupant well-being and building performance.

5.5 Concluding Remarks

This thesis demonstrated that OCC strategies, when integrated with physiological monitoring, can significantly improve comfort and productivity in office environments. The findings reinforce the importance of regional adaptation, gender inclusivity, and multi-domain comfort assessments in designing next-generation indoor environments.

By addressing key research gaps—including the climate-dependence of thermal perception, gender-specific comfort responses, and cognitive performance variations—this study lays the foundation for more inclusive and adaptive comfort models that cater to diverse occupant needs.

As building automation and AI-driven systems continue to evolve, the integration of real-time physiological and behavioral data into OCC frameworks presents a transformative opportunity for the future of smart, occupant-responsive indoor environments. Ultimately, this research contributes to creating healthier, more comfortable, and energy-efficient workplaces, aligning with the growing shift towards human-centric building design.

ETHICS APPROVAL

This protocol was reviewed by the Office of Research at Concordia University and received the Certification of Ethical Acceptability for Research Involving Human Subjects (#30016771). This protocol was also reviewed and accepted by the Institutional Review Board (IRB) at the American University in Cairo (Case # 2022-2023-069).

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APPENDIX

General survey

At the beginning of the test, the participant will read an information sheet, sign the consent form (as presented in the appendix) and start filling up the general survey here presented[1]. In the meanwhile, the researcher will associate an ID to each participant, **accounting for the information specified below** (from 1 to 3). (No personal information is included)

Experiment details – To be filled up by the researcher (single-blind study)

1. Temperature assigned to the specific test
   a) Temperature pattern a (slightly cold environment)
   b) Temperature pattern b (Neutral environment)
   c) Temperature pattern c (slightly hot environment)
2. Visual exposition assigned to the participant
   a) Exposition pattern a (first cool light, then warm light)
   b) Exposition pattern b (first warm light, then cool light)
3. Please specify in the boxes below the date and hour now:

Date:	Y	Y	Y	Y		M	M		D	D	**Hour:**	H	H	:	m	m
					-			-						:		

Instructions for participants [11]***:***

This experiment will test human thermal and visual perception under different conditions. There is no right or wrong answer. Please do not think too long about your answers, just put down whatever comes first to mind. Your participation is entirely voluntary, and you can withdraw from this experiment at any time. Your data will be stored and shared confidentially. The results of this survey will be used in presentations and publications.

You are asked to not drink any beverage or any type of food that can influence in the test results two hours before the procedure, such as coffee or alcoholic drinks. Smoking should also be avoided. Please inform the researcher otherwise.

You are asked to wear pre-defined clothes, e.g., white cotton long-sleeved shirt, long trousers, underwear, socks, sport shoes [3], to have a similar clothing insulation value for all participants. Please inform the researcher otherwise.

[1] The information sheet, the consent form, and this survey were translated to French too.

General Survey

a) <u>Demographic questions</u>

1. Which age range do you belong?
   a) Under 21
   b) 21 – 25
   c) 26 – 35
   d) 36 – 40
   e) 40 – 55
   f) Over 55
2. What is your gender?
   a) Male
   b) Female
   c) I do not want to answer
3. What is the highest degree or level of education you have completed?
   a) Less than a high school diploma
   b) High school or equivalent degree
   c) Bachelor's degree
   d) Master's degree
   e) PhD or higher
   f) None
   g) I do not want to answer
4. What is your employment status?
   a) Employed full-time (40+ a week)
   b) Employed part-time (less than 40 hours a week)
   c) Unemployed (currently looking for a job)
   d) Unemployed (not currently looking for a job)
   e) Student
   f) Retired
   g) Self-employed

5. Height:
6. Weight:

5. Please write down the country and nearest major city in which you are mainly living now.

R:

6. How long have you been living in this current city and country?
   a) < 1 year
   b) 1 – 3 years
   c) > 1 year
7. If you have been living in your current city for less than three consecutive years, please write down the country and nearest major city in which you were mainly living previously.

R:

b) Baseline behaviour and attitudes

1. Considering the last week, how was the quality of your sleep in a scale of 1 (worst) to 5 (best)?
   a) 1
   b) 2
   c) 3
   d) 4
   e) 5
2. Considering the last week, how was your stress level in a scale of 1 (worst) to 5 (best)?
   a) 1
   b) 2
   c) 3
   d) 4
   e) 5
3. Considering the last week, how were your eating habits in a scale of 1 (uncommon) to 5 (regular)?
   a) 1
   b) 2
   c) 3
   d) 4
   e) 5
4. Considering the last week, how were your exercise habits in a scale of 1 (uncommon) to 5 (regular)?
   a) 1
   b) 2
   c) 3
   d) 4
   e) 5

Please write down any further observations that you like to add:

Comfort sensibility survey

- Are you wearing glasses?

Yes ☐ No ☐

- Considering a scale from 1 (lowest) to 5 (higher), how much sensible to these thermal or visual conditions do you consider yourself?

Condition	1	2	3	4	5
Cold climate					
Hot climate					
Glare					
Bright light exposition					
Insufficient light					
Poor air circulation rate					

Perceptual survey

Thermal comfort perception preferences

1. How do you feel right now?
   a) Cold
   b) Cool
   c) Slightly cool
   d) Neutral
   e) Slightly warm
   f) Warm
   g) Hot

2. Do you find this…?
   a) Comfortable
   b) Slightly uncomfortable
   c) Uncomfortable
   d) Very uncomfortable
   e) Extremely uncomfortable

3. At this moment, you prefer to be…?
   a) Much cooler
   b) Cooler
   c) Slightly cooler
   d) Without change
   e) Slightly warmer
   f) Warmer
   g) Much warmer

4. At this moment, do you find this climatic environment…?

a) Clearly acceptable
b) Just acceptable
c) Just unacceptable
d) Clearly unacceptable

Visual comfort perception preferences

5. Do you feel that this room is…?
    a) Too dark
    b) Dark
    c) Slightly dark
    d) Neutral
    e) Slightly bright
    f) Bright
    g) Too bright

6. Do you find this…?
    f) Comfortable
    g) Slightly uncomfortable
    h) Uncomfortable
    i) Very uncomfortable
    j) Extremely uncomfortable

7. At this moment, you would prefer it to be…?
    h) Much darker
    i) Darker
    j) Slightly darker
    k) Without change
    l) Slightly brighter
    m) Brighter
    n) Much Brighter

8. At this moment, do you find this visual environment…?
    e) Clearly acceptable
    f) Just acceptable
    g) Just unacceptable
    h) Clearly unacceptable